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SPATIAL THERMAL RADIOMETRY CONTRIBUTION TO THE MASSIF ARMORICAIN AND THE MASSIF CENTRAL (France)

LITHO-STRUCTURAL STUDY

FINAL REPORT

Département carte géologique et géologie générale

Rapport du B.R.G.M.

80 SGN 848 GEO

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FINAL REPORT

by

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SOMMAIRE

pages

Report n° 3

Spatial thermal infrared radiometry contribution to the Massif Armoricain and the Massif Central (France), litho-structural study

Report date : NOVEMBER 1980

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FINAL REPORT

Abstract

This investigation is part of the HCMM NASA project. It was proposed to study on the Massif Armoricain and the Massif Central (France) test sites the value of thermal satellite date in geological mapping, structural analysis, mineral exploration and energy resource research.

Significant results have been obtained and conclusions reached open the way to promising research.

- Thermal zones delimited on HCMM images, by visual interpretation only, have been correlated with geological units : carbonated rocks, granitic, and volcanic rocks have been individualized. But rock signature is on evolutive parameter and some distinctions have been made by addition of day, night and seasonal thermal image interpretation. This analysis has also demonstrated that forest cover does not mask the underlying rocks' thermal signature.

- Thermal linears are associated with known tectonics but the observed thermal variations from day to night and from one to another represent a new promising concept to be studied in function of neotectonics and hydrogeology.

- Thermal anomalies were discovered. They represent a potential interest which is to be evaluated.

Lastly, significant results were obtained in the Mont Dore area and new geological targets were defined in the Paris Basin and the Montmarault granite, to mention the main one.

ILLUSTRATIONS TABLE

1 - HISTORICAL BACKGROUND

This HCMM project was presented to NASA as part of an investigation programme proposed by the "Groupement pour le développement de la télédétection aérospatiale" a group of scientists and engineers which coordinates the research studies in remote sensing of some major French governmental offices:

	The Centre national d'études spatiales	(C.N.E.S.)
	The Institut géographique national	(I.G.N.)
	The Institut français du pétrole	(I.F.P.)
and	The Bureau de recherches géologiques et minières	(B.R.G.M.).

Recently, the Bureau pour le développement agricole (B.D.P.A.) joined the group.

The different projects were proposed by:

1 - Dr. P. Deschamp (GROS) for oceanographic studies along the French coast lines,

2 - Dr. A. Fontanel (I.F.P.) for mineral exploration in southern France,

3 - J.-Y. Scanvic (B.R.G.M.) for rock discrimination and mineral resources in Brittany and the Massif Central,

4 - Y. Vuillaume (B.R.G.M. - G.D.T.A.) for water resource management in Brittany and the Rhône delta,

5 - Ch. Goillot (I.N.A. - I.N.R.A.) for agronomic studies.

Only two projects, according to the data utilization plan (October 1977) have been selected to explore the use of the remotely sensed HCMM data: they are projects 1 and 3.

The B.R.G.M. contract with NASA was signed under C.N.E.S. sponsoring.

From 1979, onwards, B.R.G.M. has been involved in remote sensing actively promoted by the Centre national des études spatiales (C.N.E.S.). The first experiment in thermal imagery applied to geology was acquired, with the help of C.N.E.S. for data acquisition in 1971-1972, over the "Pays de Bray", in the northwestern part of France (1). Some of the thermal pictures acquired on the test site concern the anticlinal zone of which the Pays de Bray is mainly composed. The structure is highlighted, on images, by an abrupt thermal change at the boundary of the Turonian marly chalk and the Senonian chalk, on the southern and northern flanks. This example gives an idea of rock differentiation with the use of thermal infrared. But the main interest of the study concerns a positive anomaly, near the village of Haincourt, revealed by the end-of-night summer and winter thermal images. Field checking shows the presence of Portlandian

limestones in the rare outcrops or underneath one to two meters of overburden. According to this experiment it has been concluded that thermal remotely sensed data make geological mapping possible under an overburden the maximum thickness of which is to be determined.

The aim of the J.-M. Brosse study in 1975 (2) was to confirm this ability over a test site located in the southern part of France, Les Vans (Gard - France) where quartz veins, mineralized or not, are known but generally covered by a two meters thick soil, a very frequent situation in France in the Massif Central and the Massif Armoricain. Firstly, in the field, schist and quartz vein temperatures were recorded, at three different levels (ground surface, 1 centimeter and 10 centimeters depth) by means of an automatic station, for one year. Then the thermal image acquired at the end of day and night was studied. The end-of-night image revealed a thermal linear anomaly outlining the continuity of a quartz vein intruding the schists and covered by a two meters-thick soil.

The last experiment on the topic, conducted in 1978-1979 by M.-J. Lefèvre (3) was carried out over the Coat an Noz forest, in the Massif Armoricain (France). Data was acquired by G.D.T.A. and revealed a thermal linear anomaly in the beech trees. In the field, rocks, soils, vegetation were studied and temperature, hygrometry measured. Excavations in the soil cover permitted the discovery of a granitic dyke under a three meter overburden. Highly fractured and water-saturated, this elongated granitic body is probably responsible for the anomaly. Soil temperature is similar on and outside the anomaly but leaf temperature different (of the same tree species). The conclusion reached relates the thermal anomaly with a stress acting on the leaves, increasing their temperature. This stress is probably the consequence of the high water content of the granitic body in which the anomaly trees are growing.

These three examples show the potential interest of thermal remote sensing to detect overburden geological details and distinguish between two kinds of thermal effect:

- transfer temperature from the rocks to the surface throught the covering material if it does not exceed three meters,

- stress temperature of trees.

Then, while results have been continuously encouraging, airborne acquisition is not considered realistic in an operational way because of meteorology and choice of the best flight period, a problem which has not been yet solved. For these reasons B.R.G.M. was aware of the necessity to experiment with thermal satellites and HCMM arrived just in time.

II - TEST SITE GEOLOGICAL COMMENT

The investigation has been proposed over two areas (Fig. 1):

- the Massif Central in central France (point 1),
- the Massif Armoricain, in western France (point 2).

LOCATION MAP

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

22 July 1980
METEOROLOGY C.M.S. Lannion - France -

EUROP FROM NO AA 6

The special subjects to be studied during the investigation are listed according to the instructions for the proposals, i.e.:

Geology, Mineral exploration, Energy resources.

II.1 - GEOLOGY

II.1.1 - THE MASSIF CENTRAL

The Massif Central is a highland zone of Variscan orogeny and is composed of plutonic and metamorphic rocks faulted at various epochs and partially covered by Tertiary to subactual volcanism associated with a rift system. Several tectonic basins occur moreover and are filled in with Mesozoic and Tertiary sediments.

B.R.G.M. being principal investigator (4) the Massif Central was studied during the ERTS-A investigation.

II.1.2 - THE MASSIF ARMORICAIN

The Massif Armoricain is a hilly zone of Hercynian Caledonian orogenesis composed of plutonic and metamorphic rocks and partially covered by Devono-Silurian basins. The massif is made up of three structural units:

- a northern unit, running from the "plateau du Léon" to the Cotentin area,
- a southern unit, named the "Ligerian cordillera" and giving to the Armorican region its typical parallel series feature,
- a central unit bounded by lineaments connected to two granitic areas.

The Massif Armoricain was studied during the ERTS-B investigation (5). B.R.G.M. being co-investigator in the Fralit project proposed by professor Verger.

II.2 - OBJECTIVES AND ANTICIPATED RESULTS

Five objectives were chosen as a function of thermal infrared remote sensing theoretical abilities and general geological knowledge over the selected test sites.

II.2.1 - REGIONAL THERMAL ANOMALIES AND VOLCANISM CORRELATIONS

The specific hypothesis to be investigated concerns regional thermal anomalies mentioned by professor R. Brousse (6), in the Massif Central volcanic region, over several magmatic zones he distinguished.

These zones, according to Professor Brousse, could have distinct temperatures therefore we postulated that spatial thermal infrared data could enhance the phenomenon, the large scale and the poor spatial resolution introducing - this is the basic hypothesis - a vegetation and slope levelling.

Applications concern the detection of possible potentially active volcanic zones and geothermal anomalies which until now could not be detected by using airborne infrared images.

The chosen objectives represent the main volcanic regions in the Massif Central:

- the Chaîne des Puys, near the Limagne valley, the youngest,
- the Mont Dore, a strato-volcano the activity of which began 6 million years ago and ended 500 000 years later, with a more recent activation,
- the Cantal, probably the oldest volcanic phenomenon in the region, ranging in age from 29,7 million to 3,7 million years.

The test site also includes other volcanic zones named the Limagne valley (22 to 3 million years) the Velay (13 to 6,5 million years), the Aubrac and the Coiron, etc..

Two questions are to be answered:

1 - Are the volcanic zones translated by thermal effects?
2 - Do significant temperature differences occur between the different massifs ?

II.2.2. - CARBONATED ROCK DISCRIMINATION

The specific hypothesis concerns the use of spatial thermal infrared data to discriminate limestones from dolomites outcropping equally in the Causses region (Massif Central).

The selected test site has already been investigated by airborne remote sensing and intensive field mapping. The target is made up of identified dolomitic layers in a limestone series wide enough to be surveyed by HCMM poor scanner resolution.

The application of the technique, if the experiment is conclusive, is important, dolomitic layers being a guide for mineral exploration, hydrogeology and oil exploration.

II.2.3 - ROCK DISCRIMINATION

This experiment is different from the former and concerns all kinds of rocks. The selected test sites are located both in the Massif

Central and the Massif Armoricain: rock exposures are generally poor and the idea is to look on thermal reactions of associated soil weathering and vegetation under different relief conditions or slope orientation.

Results could be important for geological mapping in poorly outcropping regions which represent an important part of the earth's surface.

The objective was chosen because Landsat image interpretation has confirmed that all over France soil and associated vegetation sometimes reflect rock differences. The expected results concern their thermal effect which could make lithological discrimination possible. Selected rock units are already identified in the field but their mapping could be improved.

A second aspect of this experiment concerns rocks' thermal inertia. This could be representative of different lithology and make identification possible.

II.2.4 - EXOTHERMIC REACTIONS AND ENERGY RESOURCES

Experiments carried out in the United States demonstrated that the heat production by pyrite oxidation may be recorded by ground temperature measurements, the thermal detected anomalies appearing to be compatible with spacecraft remote sensing.

The proposed investigations are located in open cast mines and on sulphide orebodies. All the test sites are wide enough to be consistent with HCMM spatial resolution.

In the Massif Central the selected areas are:

- Saint-Bel: pyrite deposit with important soil earth,
- Chizeuil: where several oxidizing sulphide areas are known in the vicinity of the main orebody,
- Decazeville and Montceau-les-Mines, two opencast coal mines.

Most of the test sites present anomalous heat flows.

In the Massif Armoricain the chosen site, Bodennec, is a copper deposit under investigation in the field. The extent of mineralisation is partly known and temperature measured in drilling into the orebody is not really different from the environment's but the "spontaneous polarization" is important.

II.2.5 - CHANGE DUE TO SPATIAL RESOLUTION

This part of the investigation concerns visible remotely-sensed data acquired by HCMM in the day time. Landsat images, spectral band 7 are to be compared with day visible HCMM images. Two areas have been chosen:

- Villefranche-de-Rouergue (2) a small region located in the Massif Central selected because tectonics has been carefully studied there at different scales by remote sensing: Landsat, Skylab, stratospheric balloon, aircraft images and photograhs.

- The whole Massif Central where significant tectonic and lithological features a characteristic signature on Landsat, and maps have been prepared all over the massif as part of the sismotectonic map of France (7) for tectonics, and over the western region for lithology (8), with the use of Landsat remotely sensed data.

Effects of resolution and scale change on geological details signatures are to be appreciated in this study part of the investigation.

II.3 - GEOLOGICAL BACK GROUND

Remote sensing data are difficult to check by usual field investigations so test sites have been selected according to the importance of the existing geological knowledge, acquired by way of various techniques. To each topic corresponds a series of adapted documents.

II.3.1 - REGIONAL THERMAL ANOMALIES AND VOLCANISM

Professor R. Brousse (6) prepared a volcanic map of France which shows fourteen magmatic regions in France, most of them located in the Massif Central, ranging in age from Oligocene to Quaternary. Complex details are shown on this map: eleven phases - as an example - mapped in the Chaîne des Puys from the Wurm II period (35 000 years) to the Bronze epoch (3 450 years).

In 1973, B.R.G.M. published a thermal and mineral water map (9) of France prepared by J.-J. Risler at a 1 million scale. On this document, water temperatures are indicated and in the Massif Central some of them go up to 50 centigrade and over. Other finished or underway map studies concern:

- a geothermal flux map of France (10),
- a geothermic investigation in the Mont Dore area (11),
- geological mapping at a 1/50 000 scale.

II.3.2 - CARBONATE ROCK DISCRIMINATION

Jurassic and Cretaceous carbonate layers are well exposed in the southern part of France, in the "Causses" region. Two kinds of documents are available for here:

- remote sensing data acquired by B.R.G.M. and associated companies during a three years programme, supported by C.N.E.S., of a restricted area (12). Aerial photographs, side looking radar and thermal infrared images have been acquired and rock temperatures measured.
- geological map 1/50 000 and hydrogeological map 1/250 000 (13).

II.3.3 - ROCK DISCRIMINATION

Some Caledonian granites were discriminated from the Hercynian granites, in the Massif Armoricain, by using Landsat data 1/50 000 geological map supporting these observations.

Detailed investigations at 1/25 000 scale, using various techniques, including geophysics, have been carried out on some of the granitic massifs, improving the geological knowledge of these regions.

II.3.4 - OTHER EXPERIMENTS

Local and general mapping at different scales, drilling and geophysics, support the others experiments.

II.4 - SURVEYING APPROACH

The test site was surveyed by visual interpretation of thermal images, acquired by day and night, at different seasons of the year, and documents issued have been compared with published geological maps, HCMM image distorsions making this approach difficult (Fig. 2 and 3).

Temperature differences and thermal inertia photographs were required from NASA over two scenes. Processing was experimented on, using two magnetic tapes for specific targets (scenes ID AA 009302120/3 and A 014202220/3), with the assistance of G.D.T.A. and C.N.E.S.. Lastly density slicing has been experimented on the quantitative Television microscoper.

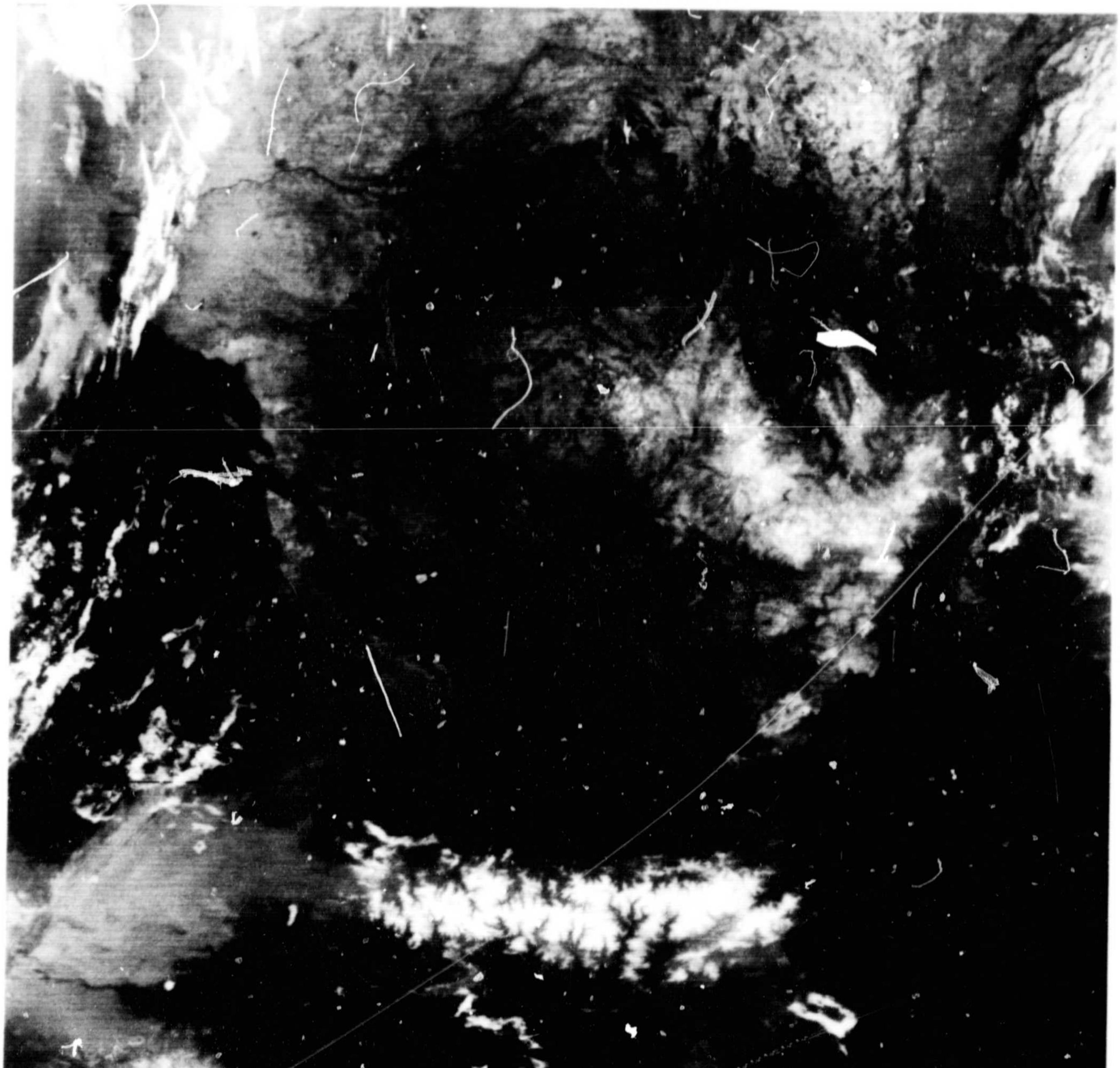
III - COMMENTS ON DATA

During the first months of the project, HCMM data were only received and distributed by NASA only, but at the end of June 1979,

FRANCE DAY IR IMAGE

17 septembre 1979
HCMM image n° AA 50912112
Day IR

FRANCE NIGHT IR IMAGE



28 juillet 1978
HCMM image AA 09302120
Night IR

the European space agency started an acquisition program with the Lannion station (France). An agreement was concluded by ESA within the framework of the Earthnet programme, with NASA, for the acquisition of HCMM data and distribution to the principal investigators whose test sites are located within the Lannion station coverage area: within this framework B.R.G.M. has received products both from NASA and ESA regularly.

Achievement of the proposed investigation was restricted by frequently unsatisfactory satisfactory cloud cover conditions. The cloud cover study carried out by NASA at the heat capacity mapping mission test site and based on Nimbus data makes it possible for investigators to determine the number of clear, or less than 30 % cloud cover cycles to be expected. Available tables (14) give 33 possibilities a year for the Massif Central and 20 for the Massif Armoricain. From US and Lannion we had already received about 400 scenes during a 24 month period starting in May 1978. ending in June 1980. About 54 scenes are acceptable but only a few are really usable (see plate 1). It has, therefore been more difficult than expected to obtain images with an acceptable cloud cover. Consequently, only two same day and night infrared images were acquired during the investigation period, the first in May 1979 covering the Massif Central test site, the second in September 1979, over the southern part of the Massif Armoricain. Thermal inertia and temperature difference images were only required on the first one (scene ID AA 038001180/3), the day image quality being poor on the second (scene ID AA 50401222/8). Such a processing was also proposed to NASA with a July day scene (scene ID AA 015112400) and a September night scene (ID A 009302120/3), weather conditions being similar; both of them were generated by NASA.

General remarks were made, from images making interpretation possible, and argued by detailed observations and comments presented in the further image analysis section.

- Day visible images contain very little significant geological information compared with :

  HCMM infrared images and
  Landsat spectral band 7 image.

However, if compared with TIROS N and NOAA visible images differences are not so important.

- Day and night infrared images contain significant geological data : in both cases, certain lineaments and rock units have a distinct signature ; day and night thermal pictures outlining different and complementary details. Seasonal changes were not completly appreciated, because of the cloud cover, but nevertheless repetitivity is very probably an important parameter, the thermal evolution making possible a more complete geological interpretation.

ORIGINAL PAGE IS OF POOR QUALITY

Plate n° 1

U.S. AND LANNION ACCEPTABLE QUALITY IMAGE

11	May	1978	3	Brittany
11	May	1978	1,2,3	South France
26	May	1978	3	Brittany
29	May	1978	3	Massif Central
30	May	1978	3	Massi. Central
31	May	1978	3	Paris Basin
15	June	1978	3	Paris Basin
17	July	1978	3	Massif Central
28	July	1978	3	Massif Central
14	August	1978	2,1	Brittany
14	August	1978	3	Landes
19	August	1978	3	West France
24	August	1978	3	Pyrenées
24	August	1978	3	Central France
25	August	1978	2,1	Brittany
3	September	1978	3	South France
4	September	1978	2	Brittany
14	September	1978	1,2	Brittany
14	September	1978	1,2	Massif Central
15	September	1978	3	Brittany
19	September	1978	3	Massif Central
21	September	1978	2,1	Brittany
24	September	1978	2,1	Massif Central
25	September	1978	3	Massif Central
25	September	1978	3	Paris Basin
17	October	1978	3	Pyrénées
31	October	1978	3	South France
1	November	1978	2,1	Causses
1	November	1978	3	Massif Central
22	November	1978	3	South France
	November	1978	3	Brittany
	February	1979	3	Brittany
27	February	1979	2,1	Pyrénées
5	July	1979	3	Brittany
5	September	1979	2,1	Paris Basin
5	September	1979	2,1	Paris Basin, South France
11	September	1979	1,2,3	Brittany
17	September	1979	1,2,3	Central France
26	September	1979	2,1	Massif Central
6	April	1980	1,2	West France
19	May	1980	3	Brittany
4	June	1980	2,1	Brittany
23	July	1980	3	Orléans
24	July	1980	1,2	Brittany, Paris Basin
24	July	1980	1,2	Brittany, Paris Basin
25	July	1980	1,2,3	North East France
25	July	1980	1,2,3	North East France
25	July	1980	1,2,3	Orléans
6	August	1980	1,2	Brittany, West France
6	August	1980	1,2	Brittany, West France
7	August	1980	2	Massif Central
10	August	1980	1,2	Massif Central
10	August	1980	1,2	Massif Central
11	August	1980	3	Massif Central
20	August	1980	1,2	Brittany
20	August	1980	1,2	Brittany
22	August	1980	1,2	West France
22	August	1980	1,2	West France
7	September	1980	1,2,3	Brittany
7	September	1980	1,2,3	Brittany
7	September	1980	1,2,3	Brittany
17	September	1980	3	Brittany, West France
20	September	1980	2	Brittany

Plate n° 2

WEATHER CONDITIONS

DATE	LOCATION	MINIMUM TEMPERATURE	MAXIMUM TEMPERATURE	PRECIPITATION	SUN INSOLATION
11 May 1978	Bretagne	8°	17°	no rain	poor
30 May 1978	Massif Central	12°	23°	no rain since May 29	poor
14 July 1978	Massif Central	3°	25°	no rain since July 12	good
17 July 1978	Massif Central	8°	34°	no rain since July 12	medium
28 July 1978	Massif Central	11°	33°	no rain on 27 and 28	good
19 August 1978	West France	9°	27°	no rain from august 17	good
15 September 1978	Bretagne	6°	22°	no rain from august 12	good
24 September 1978	Massif Central	3°	27°	no rain from sept. 21	good
14 September 1978	Massif Central	11°	25°	no rain from sept. 11	good
27 February 1979	Bretagne	3°	10°	no rain	poor
15 June 1978	Central France	11°	16°	rain after 4 dry days	poor
31 October 1978	South France	2°	19°	no rain from 26	good
1 November 1978	Massif Central	9°	16°	no rain since 26 October	good
5 September 1979	Central France	8,6°	24°	no rain from Sept. 3	poor
19 May 1980	Bretagne	8°	22°	rain	medium
4 June 1980	Bretagne	16,7°	29,6°	no rain from June 2	good

IV - IMAGE ANALYSIS

In this section it is not intended to describe all the acceptable images but only those where observations are significant enough to make appreciation on HCMM data possible. Weather conditions (Plate 2) were recorded by the meteorologie nationale (38) possible. Comments are presented in two parts, according to the location of the test sites.

IV.1 - THE MASSIF ARMORICAIN (Fig. 4)

AA 0015025250 3 - 11 May 1978 - The massif is cloud free and this night's infrared image is well contrasted. Observed geological details have a mainly tectonic origin. They are :

- the southern sillon armoricain, the main known fracture in the region,
- a series of north 140° oriented anomalies, revealed by warm linear zones, and obviously disturbing a rock unit characterized by a slight grey level difference with the surrounding. These anomalies correspond to faults called secondary by geologists but because they are associated with Tertiary grabens and considered as active faults by seismologists. Their importance has been recently recognized (15). According to published geological maps some of them have been identified (I.1).

1 - Rennes Sheet (1/80 000). The anomaly corresponds, in the Caune area, to the diabase veins' direction.

2 - Pontivy Sheet (1/80 000). Near Loudeac the anomaly is an extension of faults known into Paleozoic and responsible for Devonian bed displacements. In its western part this anomaly also corresponds to a drainage direction change, hydrography running perpendicularly.

3 - Near Saint Vran (Pontivy sheet), the anomaly follows a small Pliocene basin and corresponds to part of the Nort-sur-Erdre gravimetric axis (16) associated with a Landsat lineament (5).

4 - Near Rohan (Pontivy sheet) the anomaly bounds a small Pliocene basin and to the south, corresponds to a Landsat lineament.

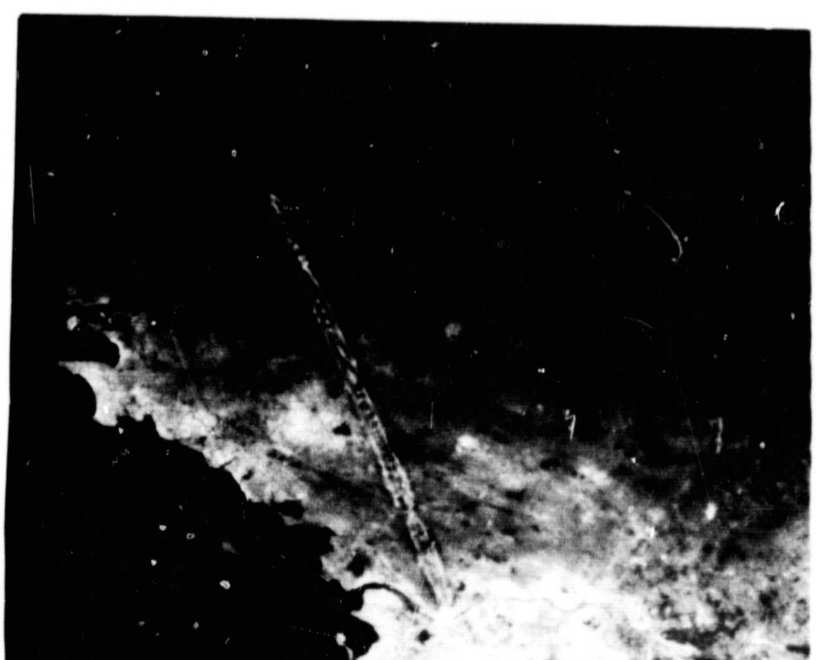
5 - To the east of Rostrenem (Chateaulin 1/80 000 sheet) the anomaly corresponds first to the Persquen fault and then to an important quartz and kersantite vein (Plouguernesel).

6 - On the Dinan and Avranches sheets (1/80 000) the anomalies are parallel to the numerous known faults.

7 - In the Plougonven region (Morlaix sheet) the anomaly corresponds to an already mapped faulted hydrographic pattern and reinforced by alluvial deposits.

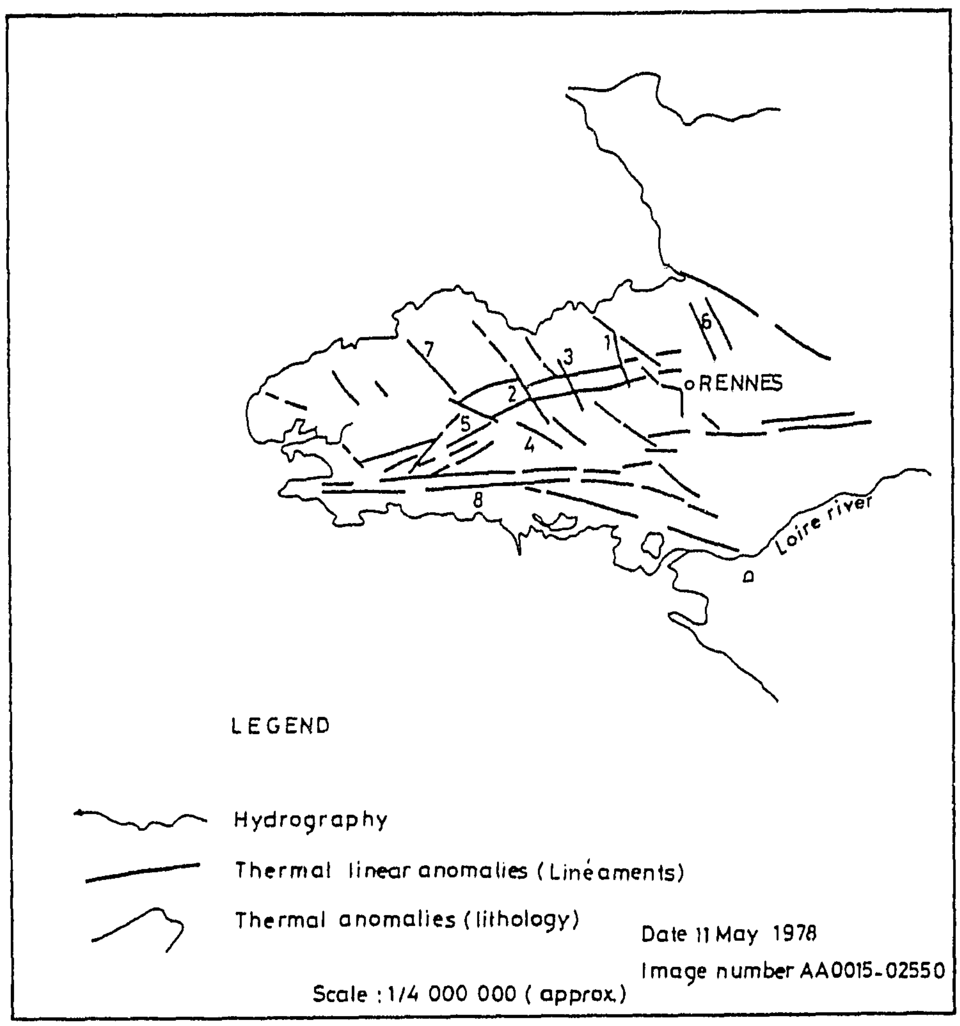
THE MASSIF ARMORICAIN

11 may 1978
HCMM image AA 001502550
Night IR



25 august 1978
HCMM image AA 012113260
Day IR

INTERPRETATIVE Map n° 1



AA 0118-13220-2 - 14 August 1978 - This uncloudy image is poorly contrasted over the Massif Armoricain. The Armorican trench is partly visible and the Quintin granite can be mapped by its thermal effect. The corresponding day image presents a uniform pale grey tone. Geological details are not revealed.

AA 0115021003 - 19 August 1978 - Is a good quality uncloudy image. It reveals the Sillon armoricain, the northern fracture of the Savenay metamorphic unit and some of the North 140° faults, all of them being warmer than the surroundings.

The Massif Armoricain generally corresponds to a level 10 grey but differentiation exists (level 5 grey) which is roughly associated with the granitic exposures.

AA 0121132602 - 25 August 1978 - Is a good quality uncloudy image. The following geological details can be mapped:

- the southern Armorican trench and parallel faulting, towards the north,
- the Savenay metamorphic rocks, bounded by faults and characterised by a slight thermal difference,
- the round-shaped Quintin granite.

On the corresponding visible image the fracture bounding the Savenay unit to the north is the only observable detail.

AA 0131 131402 - 4 September 1978 - Is a cloudy image but the Quintin and Belle Isle en Terre granite, both circular-shaped are visible. On the corresponding visible image there are no observable details.

AA 0142022203 - 15 September 1978 - Is a cloud free but not contrasted image. A few features are observed :

- part of the southern Armorican trench,
- the fault bounding the Savenay metamorphic rocks to the north. The St Georges trench. The Savenay unit itself is not visible,
- a system of north 140° trending fractures outlined by a linear warmer zone.

All over the massif, apart from these details, the apparent land temperature is uniform.

AA 0148133202 - 21 September 1978 - Is a cloud free contrasted image. The following geological details were observed :

- the southern "sillon armorican" and parallel fractures,
- the north Savenay unit fault (St Georges trench)

- the Savenay metamorphic rocks, bounded by faults but essentially differentiated by their thermal signature - level 13 grey - distinct from the surrounding one level 16 grey,
- the Quintin round-shaped granite.

The apparent land temperature over the massif, apart from the above described anomalies, corresponds to level 13 grey in the northern part and level 16 grey in the southern region but this differentiation cannot be related to a particular geological unit.

On the corresponding visible image the "Sillon Armoricain" is only locally observed and other mentioned details are not visible.

AA 43501333 - 8 - 5 July 1979 - Is a good quality night infrared image and the observed geological details have a mainly tectonic origin:

- the southern Sillon Armorican,
- the northern Savenay unit fracture ("Sillon St-George"),
- the north 140° fracturing,
- the Savenay unit has a distinct signature (grey level 13) enhanced by a narrow linear thermal zone (level 16 grey) following the already mentioned fractures,
- in the north a distinct thermal unit.

AA 50912112-7 - 17 September 1979 - Is a good quality day infrared image. The "Sillon Armoricain", the north Savenay unit fault and the Quintin granite are the only visible details.

This image analysis makes it possible to get an overall idea on thermal infrared image geological interest in the Massif Armoricain. Observations can be put into three groups:

1 - Common observations to day and night infrared images: whatever the season, the southern "Sillon armoricain" is visible on infrared images, the northern Savenay unit faults ("Sillon St Georges") and the Savenay unit itself are also visualized,

2 - Observations restricted to day thermal infrared image. The round shaped Quintin granite is never visualized by night infrared image. On day infrared images it corresponds to the western part of the already mapped Quintin granite, the circular aspect was discovered first on the Landsat image (3), recent field mapping (18) explaining this difference by a petrographic change from west to east. This feature is never observed on a visible image. North of Quintin a similar circular day thermal anomaly is also visible but only on one single image. This anomaly is associated with the Plouaret-Belle Isle en Terre granite: according to the geological map of France they have the same age and petrography,

3 - Observations restricted to night thermal infrared image.
The north 140° active faults, characterised by warm linear anomalies, are generally only distinguished on night infra images.

IV.2 - THE MASSIF CENTRAL (Fig. 5)

AA 008202080/3 - 17 July 1978 - This image makes interpretation possible over the main volcanic regions known in the Massif Central and four main geological units have been distinguished by their particular thermal signatures which reveal boundaries compatible with those of the 1 million map. These units are (I.2 and 10 b):

- the Tertiary sediments filling graben valley and associated horst; from west to east the Margeride small horst (1), the Limagne valley (2), the Ambert Basin (3) and the Roanne basin (4) are obviously separated from the other formations by their thermal effects, reinforced by faulted boundaries,
- the Causse limestones, the apparent temperature reflects the known boundaries (8),
- the metamorphic rocks Miom es Montagne) (5),
- the volcanic massifs among which are:
  - the Chaîne des Puys (1465 m), represented by a narrow warm zone, the characteristic shape can be associated with the volcanic projection making up the core of the Chaîne, this interpretation being confirmed and achieved by another image analysis (6),
  - the Cantal (1858 m) represented (7) by thermal differences which reflect alternating lava flows, the Planeze (cold) and volcanic projection (warm) reinforced by the morphology. Compared with the 1 million geological map, the interpretation is fairly good.

Other significant geological details are represented on this image, they are:

- the Sillon houiller (10),
- the Argentat fault (11),
- the Marche fault (14),

some of the main tectonic features in the Massif Central, and circular thermal anomalies located in the Forez mountains, in the Roanne basin, in the Limagne (12) north of Clermont-Ferrand, and in the Mont-Dore massif; the Villefrache-de-Rouergue structure, described by J.-M. Brosse (2), corresponds to a thermal anomaly (13).

AA 009302120/3 - 28 July 1978 (I.3.) - This image analysis is very similar to the former but :

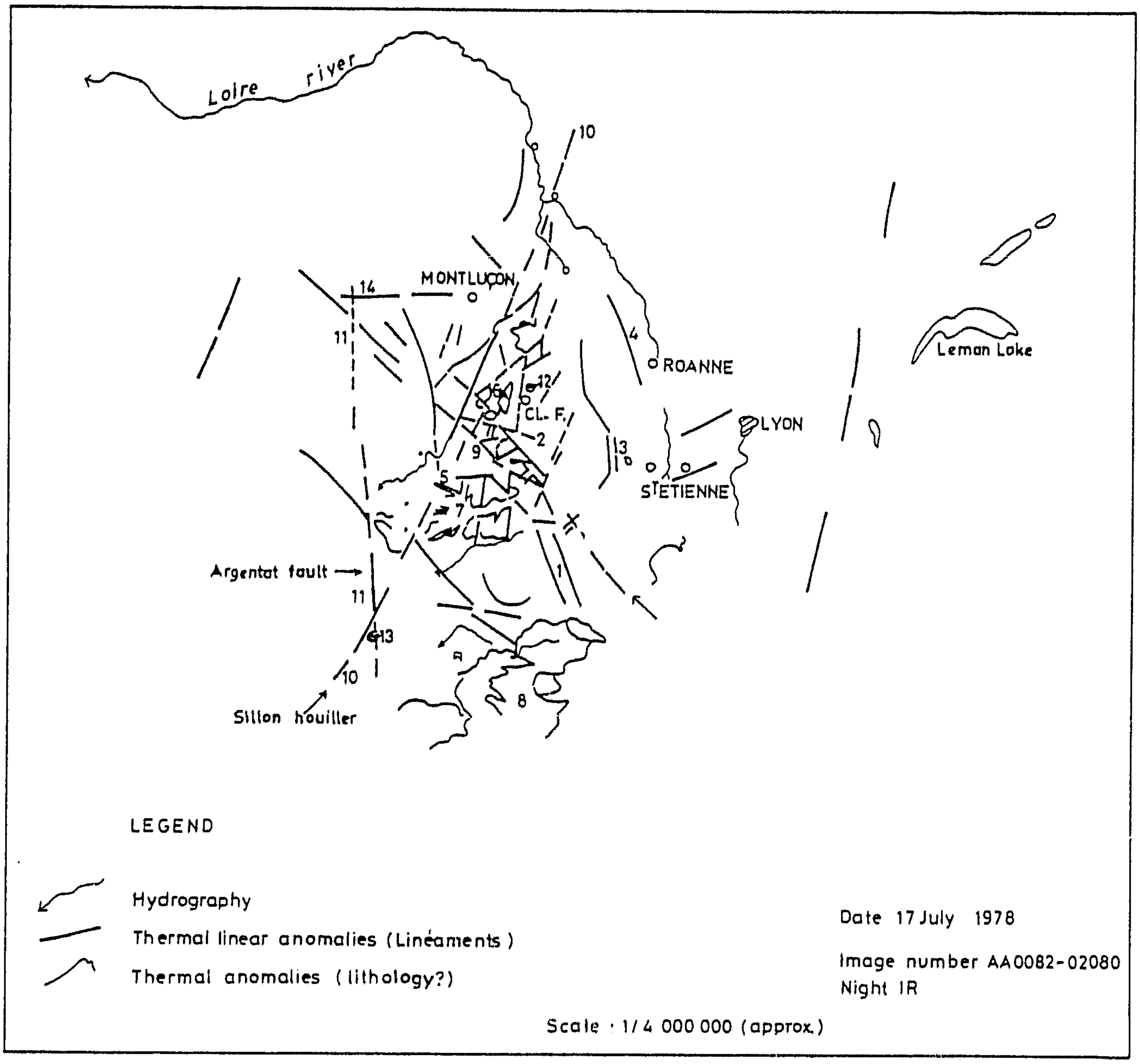
THE MASSIF CENTRAL TEST SITE

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Scale 1/ 2 000 000 (approximate)

1 november 1978
HCMM image n° AA 018901560
Night IR

INTERPRETATIVE Map n° 2



- the Mount Lozere granite (1), free of clouds here, can be separated from the Limestone - Dolomite Causse plateau (2), being colder,

- the northeastern flank (3) of the Cantal massif looks different from the rest: this thermal change corresponds to the Cezallier basaltic plateau. Then a circular thermal anomaly is observed to the south of Allanches,

- the circular anomalies discovered on the former image near Clermont-Ferrand (4) in the Forez and the Roanne basin (5) are once again represented,

- lastly, the metamorphic rocks south of Aurillac, bounded to the norh by the Cantal volcanism, also have a distinct signature.

This image has been enlarged to a 1 million scale by a photographic process. The result is satisfactory and can be superposed on to the topographical and geological maps. Magnetic tape acquired from NASA has been processed on an interactive system, the TRIM, produced by C.I.T. Alcatel and operated by CNES in Toulouse. Three kinds of process were tried out:

- dynamic optimization,
- density slicing,
- zoom.

Optimization has been carried out on a 512 x 512 line image corresponding to the Massif Central restricted test site. The approximate scale of the document is 1 million on the screen. Processing makes it possible to obtain a good visualisation of data some of them being enhanced.

Density slicing is difficult to interpret because some temperature differences only correspond to sun exposure differences.

Zoom 2, which corresponds to a 1/500 000 scale gives an acceptable enlarged image but corresponds to the maximum possibility. At least processing has been limited for only one night image was acquired on this scene.

AA 011502180/3 - 19 August 1978 - New significant details are observed on this image:

- the Miocene outcrop mapped near Bayonne: this detail is only visualized on this night infrared image, and has not been seen on Landsat,

- the Levezou basic belt. Its characteristic round shape is enhanced by thermal differences: the core is medium warm, the first ring is colder and the second warmer, the surrounding rocks having another apparent temperature,

- the granite of Clisson - Mortagne, characterized by a ring structure.

INTERPRETATIVE Map n° 3

LEGEND

Hydrography

Thermal linear (Lineaments)

Thermal anomalies (lithology?)

Date 28 July 1978

Image number AA 0093_02120

Night IR

Scale 1/4 000 000 (approx.)

Tectonic details which are visualized correspond to:

- the sillon houiller,
- the south east extension of the "Sillon armoricain".

AA 01411300-2 - 14 September 1978 - The only significant details on this image correspond to the Montagne Noire constituted by a southern unit (Cambrian) and a northern unit (migmatites) separated by a narrow Precambrian band, and to the Lodève Permo-Trias. The second has a warm signature, the first a cold signature. The Landes forest, France's biggest, in extent, made up of pine trees, and clearly visible on Landsat and other HCMM images, cannot be observed on this image but is visualized on the corresponding visible image where other mentioned details cannot be distinguished.

Other visualized details are:

- the Causses limestone plateau,
- the Sillon houiller,
- the gneiss and micaschists,
- the Jurassic limestones.

AA 015112480/2 - 24 September 1978 - Numerous significant geological details are represented on this image. From north to south they are (I.4):

- the Beauce plateau (1), the Burdigalian limestones being associated with the Upper Stampian limestones, the Aquitanian sand being separated (1 b) by their thermal appearence,
- the Berry Jurassic limestones (2),
- small Tertiary (upper) plateau near Vichy, in the Limagne valley (3),
- the volcanic Chaîne des Puys (4) minor details being represented,
- the Causse limestone plateau (5) including the western Causses of Rodez not visualized on former images,
- the Ardèche schists (6) which are colder than the Causses limestones,
- the Oligocene-Jurassic boundary on the south-west limit of the Massif Central (7, 7 b). The plateau des gras limestones (8) and associated faults,
- the Velay volcanic rocks, never observed on other images.

Among tectonic features must be mentioned:

- the Nîmes fault running to the Alps (9),

INTERPRETATIVE Map n• 4

LEGEND

Hydrography

Thermal linear anomalies (Linéaments)

Thermal anomalies (lithology?)

Date 24 September 1978

Image number AA 0151- 12480

Day I R

Scale : 1/4 000 000 (approx.)

- the North 50° Privas faults system (10), discovered on Landsat (4) and confirmed by field mapping (carte tectonique de la France),

- the Margeride Tertiary horst, cold during the day.

On the corresponding visible image, the Cantal and Mont-Dore volcanic massifs are the only significant observable geological details. C.C.T. have been required and received on this scene; processing obtained was not valuable.

AA 015202100/3 - 25 September 1978 - This image is free of clouds but the quality is not the best over test site. Significant details are:

- the Margeride Tertiary horst, warm at night. Its tectonic relationship with the Mont-Dore volcanic massif is very obvious,

- recent Quaternary near Tarbes,

- the small Permian outcrop located north of Castelnau,

- the Clisson's granite,

- the Sillon houiller,

- the north Pyrénées overthrust.

AA 018901560/3 - 1 November 1978 - Significant details are the following:

- the Coiron volcanic rocks (1) the typical shape is enhanced by thermal difference with the underlying sedimentary unit, (I.5),

- the Tertiary horst and grabens (Roanne (2), Ambert (3), Limagne (4), Margeride (5)). In particular the southern fault of the Margeride horsts obviously extends towards North west, bounding the Cantal Massif to the North, ending on the Sillon houiller. On this image tectonic relationships between the Margeride horst and the Mont-Dore volcanic rocks fracturing are evident,

- the Mont-Dore massif,

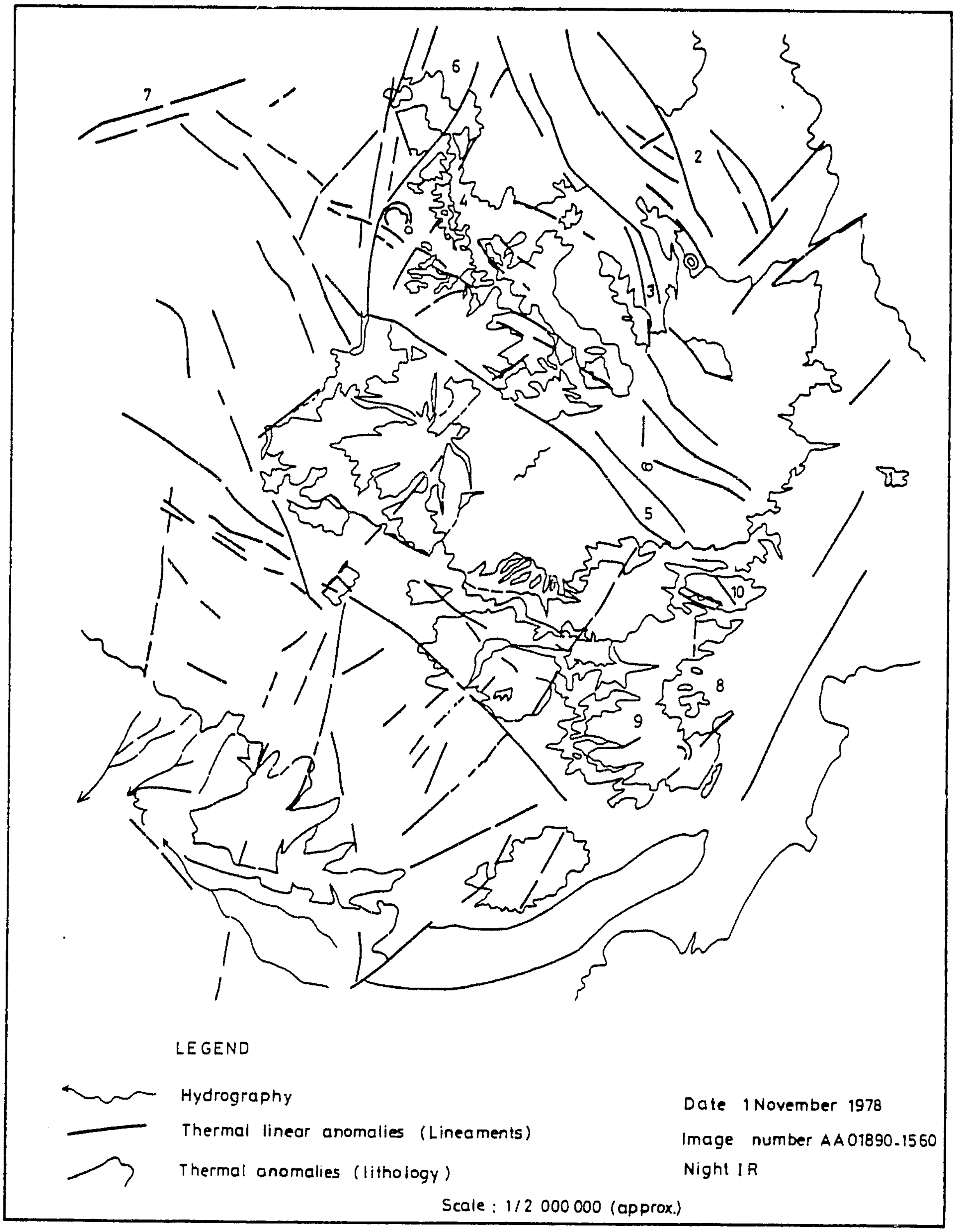
- the Permian outcrops near Castelnau,

- the Cezallier volcanic rocks.

Others thermal differences are:

- the circular thermal anomalies in the Forez mountains, north west of the Mont-Dore massif (near the Sillon houiller) and in the basin d'Ebreuil (6) (a new one),

INTERPRETATIVE Map n° 5



- the Sillon houiller, the Marche fault (7) represented by two parallel warm linear anomalies,

- the Ardèche schists (8) (warm) the Causse plateau (9) (cold) the mount Lozère granite (cold) (10), the Cretaceous "plateau des gras" limestones (near Aubenas) and associated faulting.

AA 03071551-8 - On this night infrared image acquired by the Lannion station interpretation is not possible on the test site but significant geological details exist to the north:

- the Paris Basin Tertiary layers (warm), this image makes it possible to obtain with thermal remote sensing an acceptable mapping of this region if combined with others,

- the Berry Cretaceous limestones characterised by scattered warm zones. This image is the only one where they are visible, even on uncloudy documents,

- the Rouen - Les Andely fault with an important extension to the south east.

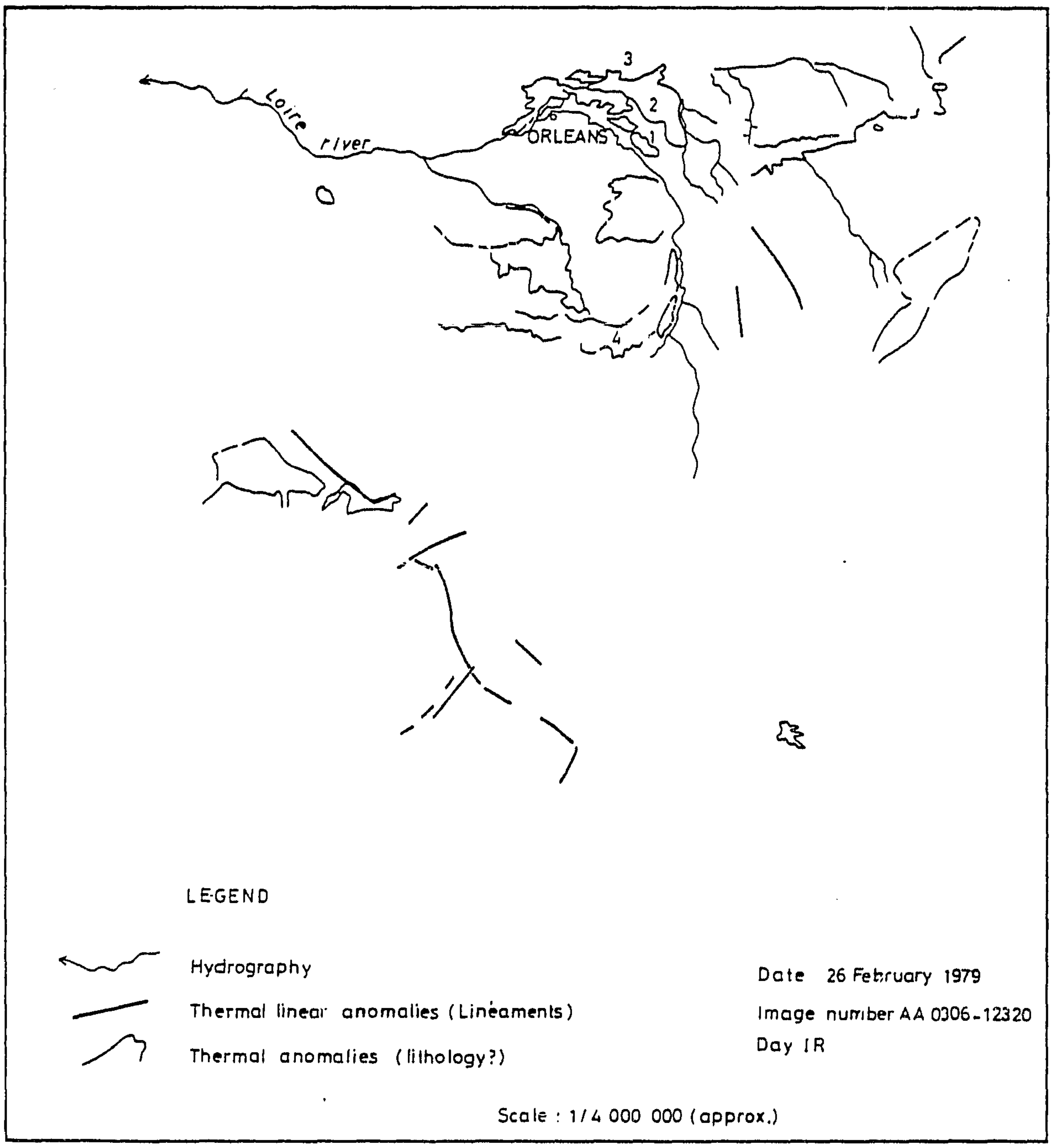
AA 0306-12320/2 - 26 February 1979 - This image (I.6) has been selected for, to the north of the Loire river thermal differences enhance subtle geological differentiations, the Orleans forest effect being partly levelled. This interpretation is compared with the AA 0151-12480/2 - one - Significant results are summarized on the next figure. They illustrate the interest of thermal seasonal evolution in geological mapping.

Geology (19)	AA0306 (February)/2	AA0151 (September)/2
Quaternary (Val de Loire)	Cold, then the difference with Aquitanian sand is not obvious	Warm, then this unit is clearly distinct from the Aquitanian sand
Aquitanian sand (1)	Cold	Cold
Burdigalian limestone (2)	Warm	Undifferentiated and warm
Stampian limestone (3)	Cold	

Moreover a new discrimination has been made in the Berry Jurassic limestones (4).

AA 030001180/3 - 11 May 1979 - Significant results obtained on this image concern geological details already discussed but the Levezou domain structure is there obviously represented by it thermal (cold) signature.

INTERPRETATIVE Map n° 6



AA 43501333-8 - 5 July 1979 - (I.7) - This is a night infrared image covering a large area over western France and acquired by the Lannion station. This picture is not specially interesting from a lithological point of view, few details being observed, but structural geology is particularly well visualized. Among the numerous details which have been observed have been selected:

1 - the Thouarce-Montreuil-Bellay fault (thermal high),

2 - a north 140° fault, running from north to south across the Massif Armoricain, partly associated with a Landsat lineament and an aeromagnetic discontinuity (thermal high),

3 - the "Saint-Georges'sillon", bounding to the north the Savenay metamorphic (thermal high),

4 - Noirmoutier island is not visible,

5 - the Niort fault (thermal low),

6 - the Marche fault (thermal high),

7 - the Vilaine river fault (thermal low),

8 - the Nogent-le-Rotrou fault (thermal low),

9 - the "Sillon Armoricain", composed of a narrow band enhanced by a thermal high (North west) and then by a linear frontier between a thermal low (to the North) and a thermal high (to the south),

10 - the Pays de Bray fault (thermal high),

11 - the Sillon houiller (thermal low),

12 - a north 110° fault, running across the Paris Basin (thermal low).

Some others details correspond to:

13 - thermal differentiation in the sea, in the "baie de Seine",

14 - towns - Paris for instance, associated with a thermal high, the small thermal low (15) possibly outlining the forest,

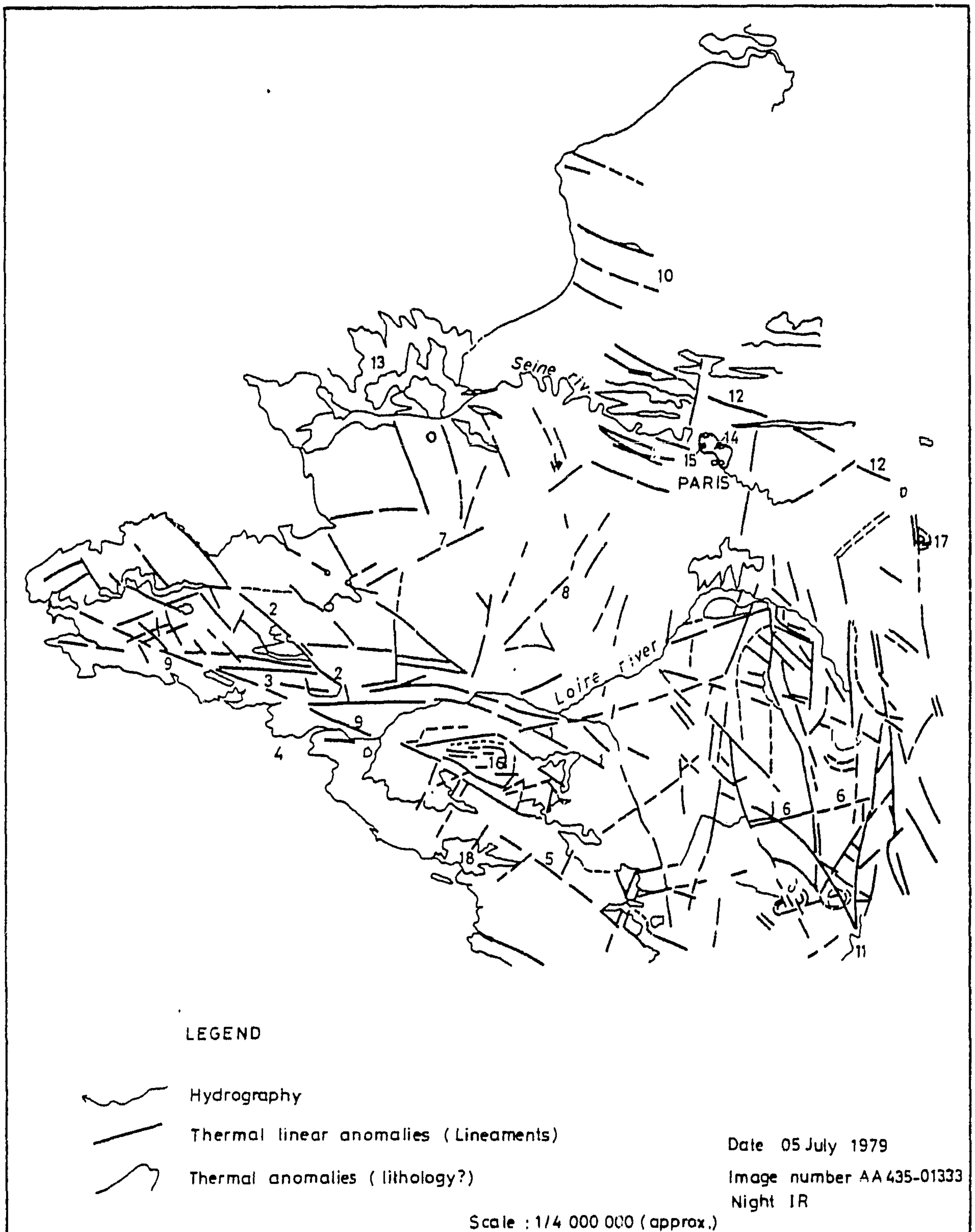
16 - circular features composing the Mortagne granite,

17 - other circular structures,

18 - the Niort swamp.

AA 504012228 and AA 504 12224-7 - have been acquired on the same day, 12 September 1979, but the major part of the day infrared is cloudy on the test site (Massif Central).

INTERPRETATIVE Map n° 7



AA 509-12 112-7 - 17 September 1979 - This infrared day image presents a global view of France. Significant geological details are visualized by their thermal signature. They correspond both with lithology and tectonics (I.8.a).

Lithology

- the Bray anticline limestones (1), the core presents a thermal differentiation (20),
- the Ardennes mountains (2) the Jurassic "biseau" (wedge) known on its southern flank, being very obvious (3),
- the Tertiary (4) Cretaceous (5) and Jurassic (6) stratas forming the Paris Basin,
- the Berry Jurassic limestones (7),
- the northen part of the Morvan cristalline rocks (8),
- the volcanic Chaîne des Puys (9) the basaltic flows preserved in the Limagne valley being visible (Chataugay, Gergovie, etc.).

Tectonics

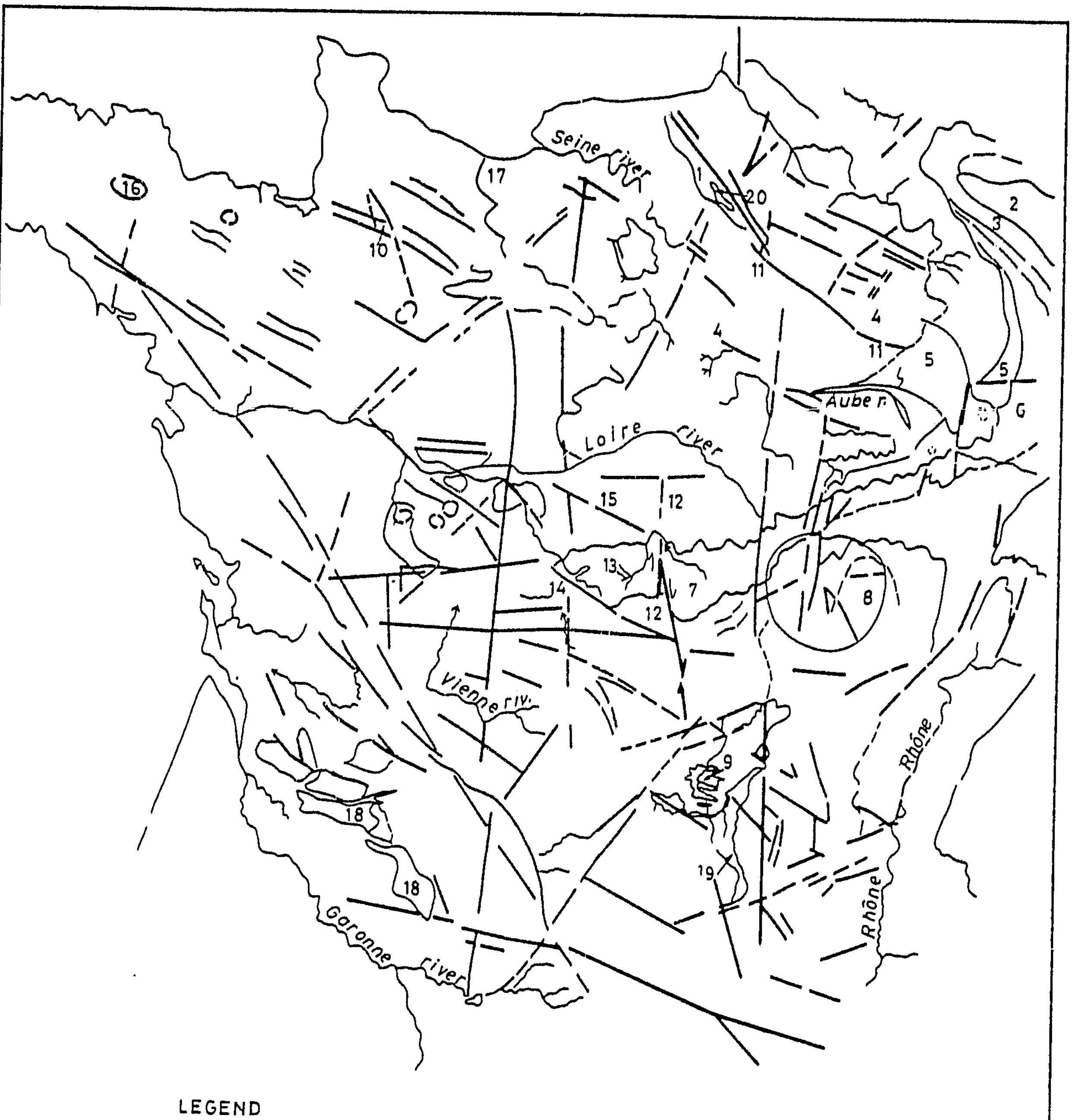
- the "Sillon d'Avranches" (10),
- the Bray fault and its southeastern extension (11),
- the Issoudun Sennely fault (12) which seems to create a northern displacement of the western Berry limestones (13),
- the Indre fault (14),
- the Tours-Bourges anomaly (15) which corresponds, according to the tectonic map of France (24) to the maximum subsidence known in the area, the basement being at 1 500 m, and also with the known western limit of the Permian recognized by drilling and geophysics.

And some others details:

- the Quintin granite (16),
- a Jurassic Cretaceous boundary (17),
- the Libourne Miocene (18),
- the Limagne valley (19).

AA 509 011171-8 - 17 September 1979 - This infrared night image presents a global view of France. It is probably the best one acquired over the country (Fig. 5b) and very significant geological details have been recognized by their thermal signatures. They correspond both to lithology and tectonics (I.8.b).

INTERPRETATIVE Map n° 8a



LEGEND

Hydrography

Thermal linear anomalies (Lineaments)

Thermal anomalies (lithology?)

Date 17September 1979

Image number AA 509-12112

Day IR

Scale : 1/4 000 000 (approx.)

INTERPRETATIVE Map n° 8b

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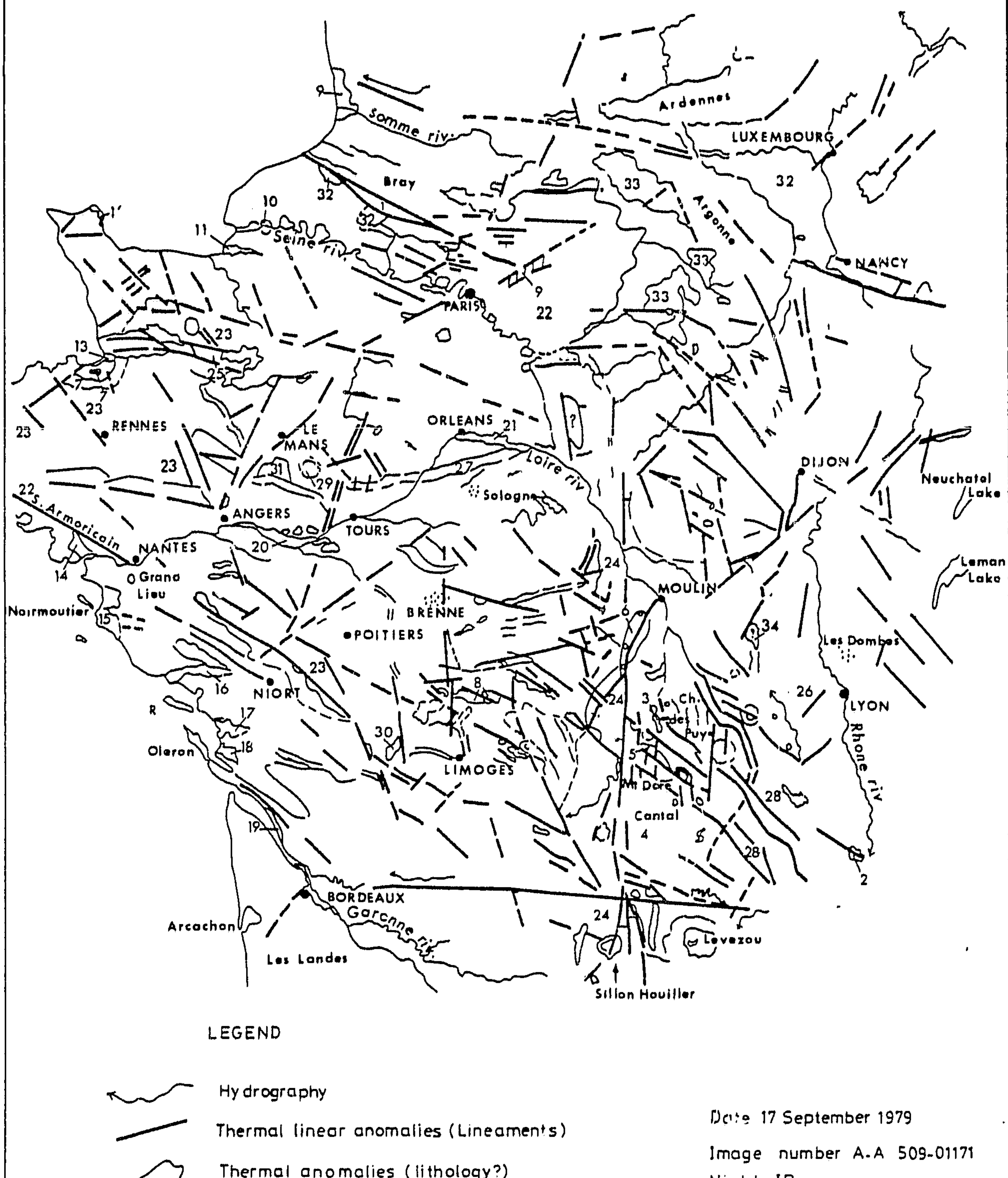


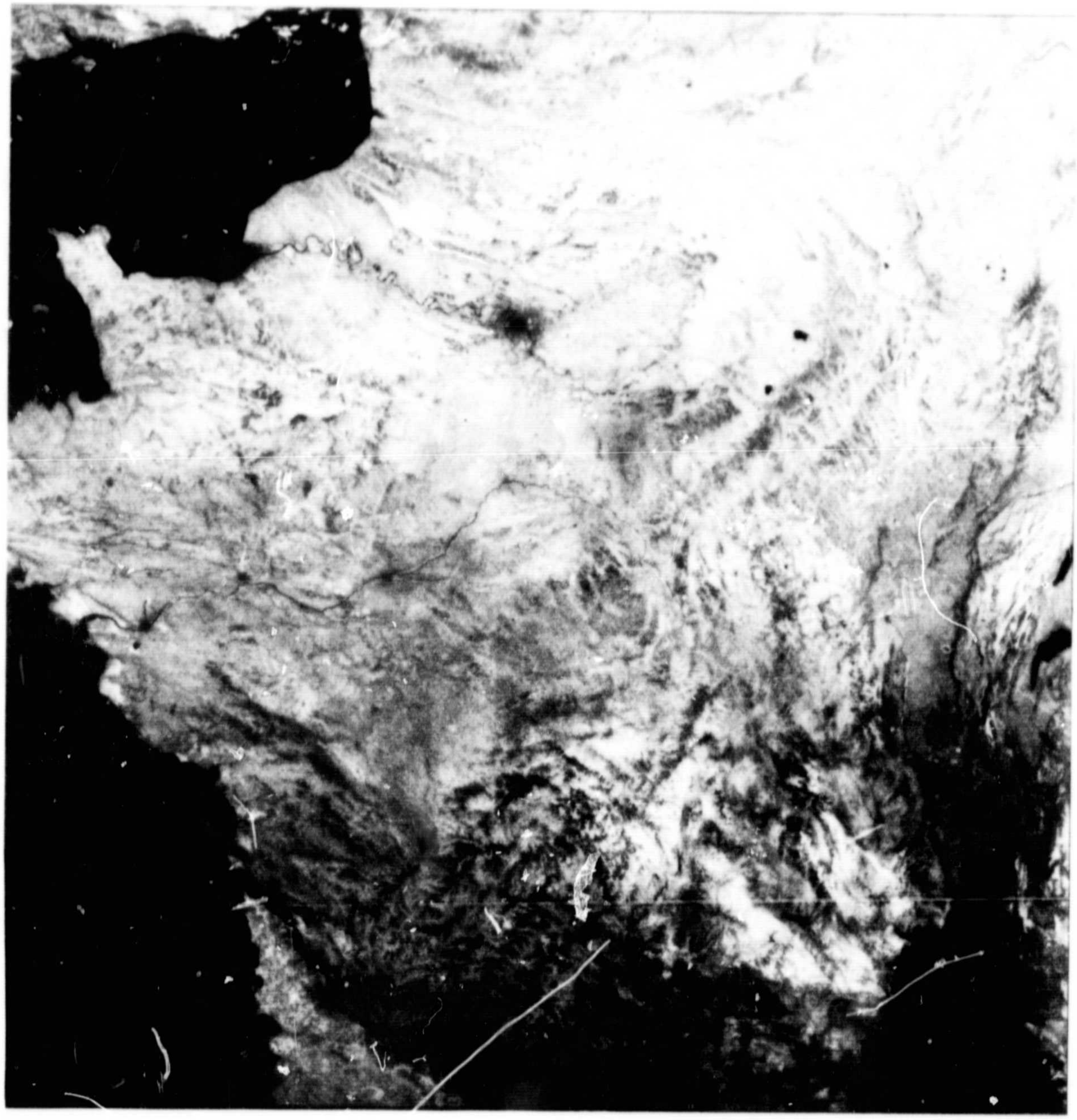
Date 17 September 1979

Image number A-A 509-01171

Night IR

Scale: 1/4 000 000 (approx.)

FRANCE NIGHT IR IMAGE



17 september 1979
HCMM image AA 50901171 3
Night IR

Lithology

The more visible details concern:

- the Bray anticlinal limestone (1) (thermal low),
- the volcanic rocks: Coiron (2) (thermal low), Chaîne des Puys (3) (thermal high), Cantal (4), Mont-Dore (5),
- the main lava flow, in the Cantal-Cezallier area is pictured with a thermal low,
- the Montmarault (6), Dole and Dinan (7) and Ambazac (8) granites which are represented by a thermal high. The small granitic body "des Pieux" near Cherbourg, pictured by a thermal low,
- the coastal Quaternary and swampy area, from north to south in

Berck (thermal low) - 9 -
Le Havre (thermal low) - 10 -
Cabourg (thermal low) - 11 -
Ste-Mère-l'Eglise (thermal low) - 12 -
Mont-St-Michel (thermal medium high) - 13 -
St-Nazaire (thermal high) - 14 -
Challons (thermal high) - 15 -
Niort: this swampy area, probably the largest, is the least visible.

Thermal constrat with the surrounding limestones being not very important (16),

Rochefort (thermal high) - 17 -
St-Aignant (thermal high) - 18 -
La Gironde (thermal high) - 19 -

Alluvial river deposits are visible along the Loire river east of Angers (20) and Orleans (21) where they are quite extensive (7 km wide): they have a thermal medium low.

Lastly, far more lithological features are represented on this exceptional thermal image.

Tectonics

Among tectonic features the following have been selected.

The "Sillon Armoricain" (22) and possible extension towards the south east, represented by a thermal high.

Some of the North 140° neotectonic faults (23, thermal high).

The Sillon Houiller (24), which has a composite thermal expression:

thermal high in the south (Villefranche)
thermal frontier in the Cantal area
thermal high in the Mont-Dore area
thermal low in the St Eloy area
thermal frontier in the Sancerre region.

The Sillon d'Avranches (25), which is revealed by a thermal high.

The Brevenne (26) (thermal high).

In the Sologne (27) a 3 km thermal low zone bounded by thermal high linears on both sides extends for 50 km. This zone follows a boundary between terraces to the north and Miocene to the south and could represent an overburden graben, oriented, according to a fault direction known in the basement (La Marche).

In the Mont-Dore, Margeride (28) area the fracture pattern (North South and Armoricain) is clearly pictured and suggests that the North South faults have displaced the Armoricain one.

Lastly a lot more structural details are visible on this image.

Circular features

Two of them are particularly interesting.

- One in the Montmarault granite (35) which is represented by a thermal medium high, with a thermal high ring. This structure could correspond to a circular pattern observed on aerial photographs and Landsat (36) image which has been studied in the field and identified as a Caldera (37).

- The second is a 45 kilometers circular zone (29), North Château du Loir, enhanced by a thermal high ring. This very characteristic feature, crossed by National road 158 Le Mans Tours, is located in Cretaceous limestones. No explanation has been found as yet.

Other features

Some thermal differences which are observed at different seasons have not been yet explained by lithology, structure or climate. These discordant features are probably the most promising.

On this image some of them have been delineated and compared with maps:

- North of Roanne (24) where a thermal high zone is included in Jurassic, apparently homogeneous limestones in which some granitic bodies are outcropping.

- South west of Limoges (30) where a thermal high zone is observed in the metamorphic schists series which includes granitic bodies.

In these two examples the size of the phenomenon and the landscape make it possible to exclude a local climatic effect.

- North of La Fleche (31) where a thermal high presents a very definite shape included in Cretaceous partly covered by Eocene in the central zone. This effect could correspond with the Eocene erosion surface.

- In the western part of the anticlinal de Bray (32)

- In the Cretaceous chalk of the Paris Basin (33).

FEBRUARY 1979, a night IR image (I.9) This night infrared image has been acquired by the Lannion station. Among significant geological details, the following have been selected :

1 - the Tertiary unit forming the Paris Basin, associated with a thermal high. This is the only image making possible a near complete mapping of this unit,

2 - the Cretaceous of the Berry region (thermal high). In general only the Berry Jurassic limestones are observed, and during the day,

3 - the Miocene of the Orleans area (thermal low) with a differentiation (4) in the vicinity of Orleans (thermal high),

5 - the "Sillon armoricain" (thermal high),

6 - the Thouarce Montreuil Bellay fault (thermal low). It is interesting to notice that this fault, in July, and also during the night, is associated with a thermal high.

7 - the Les Andely fault and its eastern extension, associated with a thermal low,

8 - On both sides of the Les Andely fault, and in sedimentary rocks, a circular structure is observed and even seems to be displaced towards the west at the northern limit,

9 - A contact between Cretaceous and Jurassic levels.

Lastly, as far as meteorology is favourable, this period of the year makes it possible to observe fairly interesting details.

INTERPRETATIVE Map n° 9

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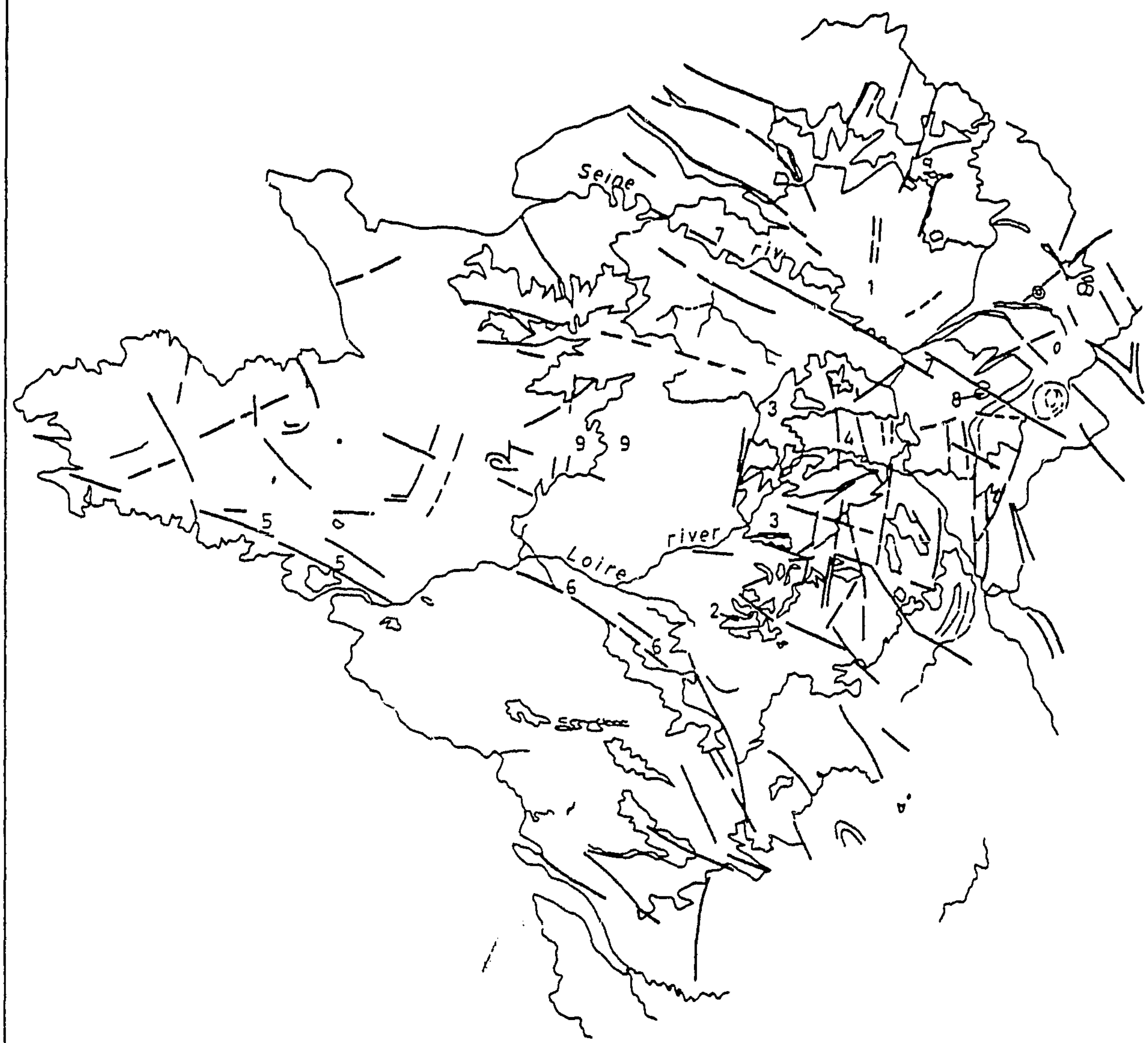


LEGEND

Hydrography

Thermal linear anomalies (Lineaments)

Thermal anomalies (lithology?)

Night IR

Date February 1979

Scale : 1/4 000 000 (approx.)

This image analysis reinforces the conclusions reached on the Massif Armoricain test site:

. Significant details are visualized on both day and night infrared images, the Cantal massif, the Paris Basin sedimentary levels for instance, but in general and this has not been explained yet, the observed geological details are more numerous and more constrasted over the Massif Central.

. Some lithological units are only visible on day infrared images: the Berry limestones.

. Some lithological units have been only observed on night infrared images, the Levezou basic belt, the Mortagne, Ambazac and Montmarault granites.

. Some complex units have been mapped by using day and night complementary information (Chaîne des Puys) or seasonal complementary information (Causses plateau), water content playing a certain role (Orleanais).

. Thermal inertia affects the thermal signature, making possible important lithological differentiations.

. Some thermal high zones are not explained by lithological changes or climatic effects: they open an interesting research.

. Linears have different thermal signatures.

V - PROPOSED HYPOTHESES AND RESULTS OBTAINED

In this section the proposed hypotheses (chapter II.2) are confronted with the thermal data interpretation.

V.1 - THERMAL DATA ANALYSIS GENERAL REVIEW

The analysis has been limited to the standard NASA and Lannion photographs with three exceptions only:

1) The thermal inertia and temperature differences calculation and photographic visualization carried out by NASA, and discussed in part V.1.5.

2) A density slicing carried out on two scenes with the CNES interactive system (TRIM) and the B.R.G.M. Quantitative Television Microscope. This kind of processing has been proved uninteresting, the slicing

still being chosen on the grey level scale printed on the photographs. Actually the density slicing obtained in this way cannot be correlated with the lithology, this being possible by visual differentiation.

3) A derived type image was processed with the Quantitative Television Microscope. This kind of processing was an improvement on fracture analysis.

Thermal zones were analysed and some of them were mapped. Observed temperature differences are generally explained by the following phenomena.

Meteorology

This kind of thermal zone was divided in two categories.

- The first one presents diffuse boundaries and covers a wide area. Its appearance is very characteristic and it generally lies along a river (Rhone Valley) or over a wide forested area (Landes).

- The second one presents very clear boundaries generally accentuated by topography; this kind of thermal difference was observed in the Ardeche area on night image AA 009302120 July 8, 1979. The phenomenon is characterized by a sharp frontier between a thermal high (Rhone Valley) and a thermal low (Massif Central) running along 160 km. This difference follows pretty accurately a drainage basin change, the Ardeche Mediterranean one (the warmer) to the east and the Atlantic one (the colder) to the west and from a meteorological point of view this phenomenon is very well known. Other similar atmospheric effects have been observed on the southern limits of the Cantal Massif and west of the Sillon Houiller (near St-Eloy-les-Mines) but for these two examples the phenomenon is probably more complex and fault existence is not excluded and could be reinforced by meteorology and topography.

Topography

In the mountainous areas, the Alps, the Pyrennees it was difficult to outline significant thermal differences except for those of tectonic origin.

In the areas of average relief the value, in terms of geology, of the thermal zones, is a function of the orientation, even on night images. For instance, in the Massif Central, the lava flows in the south west and in the west are associated with a thermal high, but on the eastern and northern limits there are represented with both schists and granites, with a thermal low. Under such circumstances all preserved thermal highs are very interesting: the Morgewd fault system and some circular structures for exampl^-. Finally most of the significant results were found in low relief areas.

Vegetation

On the night infrared image forested areas are generally represented by thermal lows whatever the trees are, coniferous or deciduous. Such a signature was observed over the Landes, the Sologne, Orleans etc. forests.

But some forests, Argonne, Othe associated with a medium relief and a specific lithology, are represented by a thermal high. Under these circumstances the forest signature is combined, or cancelled with or by the basement signature and this observation is considered as very significant for the geological interpretation of some thermal differences.

Humidity

At certain seasons some of the geological units are more or less impregnated with water. Very subtle lithologies were delimited during the rainy period of the year because their water content had effected the thermal response, for instance in the Orleans region where some sandy units were discriminated.

Albedo

Accurate differentiations were achieved over the Causses plateau, the Berry, the Chaîne des Puys where the rocks albedo is a predominant factor.

Thermal inertia

Most of the lithological differentiations were made possible because the observed thermal differences change from day to night and from summer to winter. Also geological mapping from thermal images was possible and results are significant, compared to compatible scale maps as far as a representative set weather conditions set of day and night images has been interpreted.

The thermal zones were compared with geological maps to check the value of the proposed hypothesis, regrouped, to simplify the presentation, into two categories: rock discrimination and exothermic reaction.

V.2 - ROCK DISCRIMINATION

Fairly obvious correlations were observed between thermal image interpretation and compatible geological maps. In this section observations made during the analysis phase are presented and discussed.

V.2.1 - CARBONATE ROCK DISCRIMINATION

In this section we intend to discuss with examples, the ability of thermal remote sensing to discriminate limestones and dolomites, a conclusion reached by L . Rowen T. Offield and K. Watson (20) on a U.S. test site.

Dolomites being considered as an important guide in energy resource prospection, geologists and remote sensing scientists have experimented all available techniques making this differentiation possible. Max Guy (21) used successfully infrared colour photographs, in the Pyrennees mountains, to discriminate limestones from dolomites and later Berthiaux (22) reached the same results in the Arabian Peninsula.

The selected test site is located in the southern Massif Central, in the Causses plateau where dolomites and limestones outcrop fairly widely. During the ten past years different remote sensing techniques have been experimented on and geological mapping is very detailed.

1) Colour and infrared colour aerial photographs were acquired at a 1/30 000 scale. A photogeological map and field control were made and from these three dolomitic layers were distinguished by colour and morphology.

2) Day and night infrared coverage has been realized with a scanner Cyclope (3 - 5 micron) and Super Cyclope (8 - 14 micron). On these images limestones can be differentiated from schists and granites and sink holes have a distinct signature. The associated faults are delineated as thermal lows or highs.

3) Side-looking airborne radar has been experimented on at the test site. Both Goodyear and Vigie Thomson 3 centimeters wavelength and JPL 26 centimeters wavelength images (normal and cross polarization) have been acquired and compared (23). All images make it possible to discriminate carbonate rocks from schists and granites by way of surface roughness.

4) Landsat images have been studied, seasonal and multispectral effects making possible differentiations in the carbonate Causse plateau series. The main result was obtained on the 19 September 1976 scene (orbit 21 277, cycle 85), differences occurring on spectral band 5 which are more or less associated with the lower and medium Jurassic boundary, as mapped on the 1 million geological map of France. Vegetation being very scarce all over the Causses plateau the change is a function of rocks' albedo differences.

Day and night HCMM images, acquired at different epochs, make possible a significant interpretation summarized on plate n° 3. According to this a dolomite-limestone discrimination is feasible but a few comments on conclusions are necessary:

THERMAL EVOLUTION OF ROCKS CONSTITUTING THE CAUSSES AREA

Plate n° 3

Date	Day or night I.R.	Carbonate rocks forming the Causses plateau A	Lower Jurassic (Mainly limestones) B	Medium and upper Jurassic (Mainly dolomites C	Schists D	Granites E	Carbonate rocks and granites associated F
17 July 78	3	thermal low (détroit de Rodez missing)			thermal high	thermal low (more than A)	
28 July 78	3	thermal low (détroit de Rodez missing)			thermal high	thermal low (more than A)	
14 Sept. 78	2		thermal low not distinct from surrounding	thermal high	thermal low	thermal low, not distinct from D	
19 Sept. 78	3	thermal low			thermal high	thermal low (more than A)	
24 Sept. 78	2	thermal high			thermal low	thermal low. Not distinct from D	
25 Sept. 78	3	thermal low					
30 Sept. 78	3				thermal high		thermal low
1 Nov. 78	3	thermal low			thermal low (more than A)		
7 Aug. 80	2	thermal high		thermal high	thermal low		

1) Warmer during the day, the carbonate rocks forming the Causses plateau are colder than the surrounding schists at night. This visual appreciation is corroborated by field measurements (2 and 12) carried out in that area between August 1973 and September 1974. In September the average temperatures were:

43° celsius during the day
20° celsius during the night, for the limestones and
25° celsius during the day
35° celsius during the night, for the schists.

2) A few days' interval (14 to 24 September 1978) made it possible to separate the Causses plateau into two thermal zones by superposition of the interpretations: the eastern zone is warmer, the western is colder.

This difference, first of all, is not ascribed to vegetative cover or slope changes, these parameters being the same on the two thermal units.

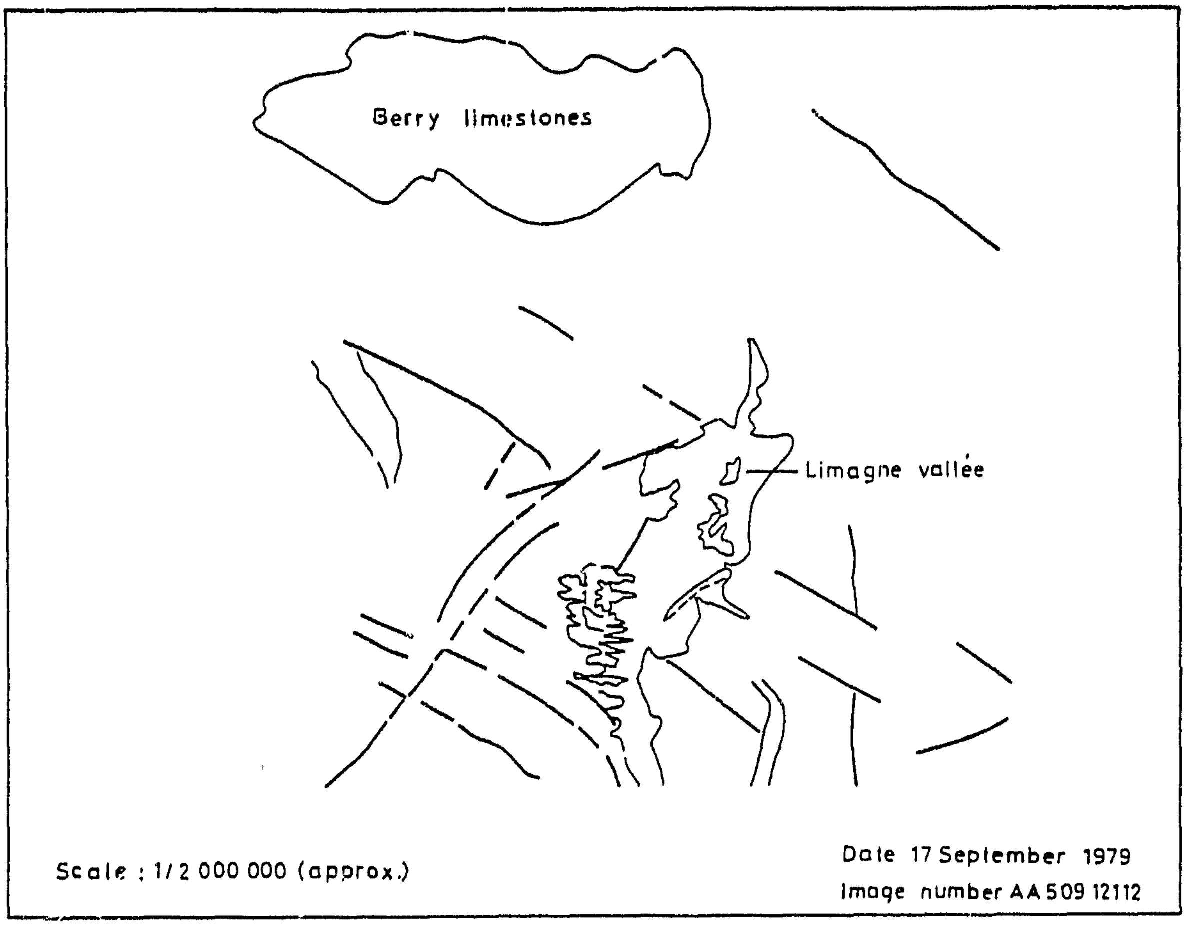
On the other hand, weather conditions according to the "résumé mensuel du temps en France" (24) are very similar and rainfall cannot be responsible for the difference. According to field measurements (plate n°2) weather conditions were the following.

minimum temperature 11°	(14 Sept)	12°1	(24 Sept)
maximum temperature 25°	(14 Sept)	27°2	(24 Sept)
insolation sunshin 119	(14 Sept)	110	(24 Sept)
rains	no rain for 3 days	no rain for 3 days	

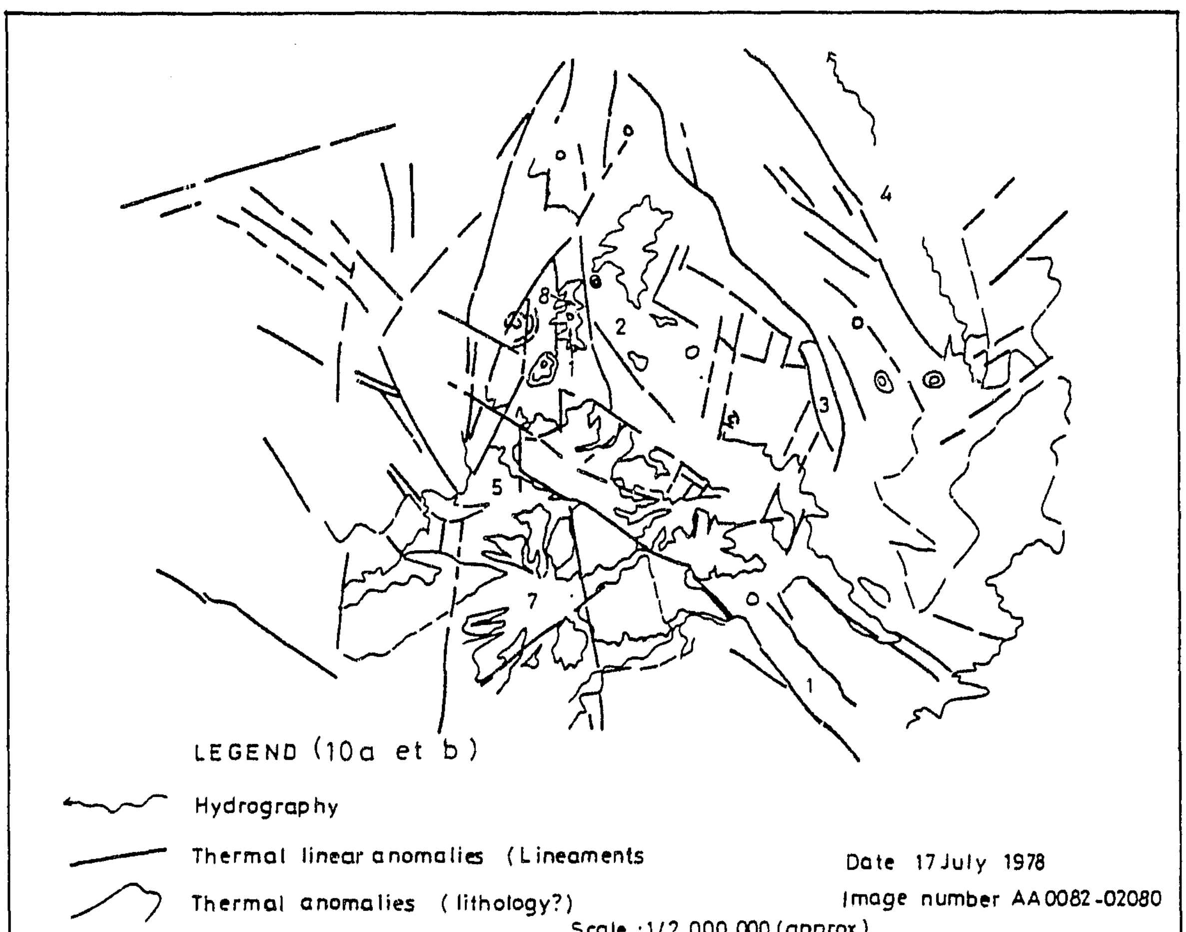
By comparing the two thermal zones with the geological mapping (13) it is possible to assume that the temperature difference is associated with colder dominating limestone, to the west, and warmer dominating dolomites, to the east. But if thermal inertia value is the only parameter influencing the signature this conclusion is opposite to the expected one, limestones being generally considered as warmer than dolomites during the day. Actually, according to Landsat, the dolomitic layers present a high albedo, compared to the limestones, and thermal conditions are different as demonstrated by Clark (25) and Rowan (20): during the day albedo and thermal inertia work against, if the lower albedo is paired with a higher thermal inertia and then maximum contrast is expected at night time. But if a high albedo is paired with high thermal inertia it provides a maximum day time contrast, if the effects of the topography do not overwhelm the observed thermal distribution.

Finally this explains the thermal visualization of dolomite on the September, 14 image, but not the lack of temperature differences between limestones and dolomites on September 24. Actually only water content could reasonably explain such a discrimination : according to measurements taken at the two nearest meteorological stations, Mont Aigoual and Mende, rain was observed on September 11 and later on September 27.

INTERPRETATIVE - Map n° 10a



INTERPRETATIVE Map n° 10b



V.2.2 - VOLCANIC ROCK DISCRIMINATION

Two problems are examined in this section.

1. delineation of volcanic rocks from others
2. discrimination, according to the Brousse concept (6) of different magmatic zones characterized by distinct temperatures.

1. Image analysis makes it possible to delineate thermal zones which, according to geological maps, reproduce some of the main volcanic units known in the Massif Central.

- The chaîne des Puys, composed of various Quaternary volcanic rocks is associated with a thermal low in the day time, a thermal high at night but:

. on day image (Fig. 6a) basalts and scories (point 1, I.10a) combine their thermal signature,

. on night image (Fig. 6b) only the scories are observed (point 1, I.10b). Moreover, on the day image small details have been delineated, mainly the narrow flows going down from "the Chaîne des Puys" to the Limagne Valley: Volvic, Chateaugay, Gergovie... According to Landsat, albedo plays an important role in this discrimination, the "Chaîne des Puys" having a low reflectivity which contrasts with the underlying rocks.

- The Cantal massif, composed of various Tertiary volcanic rocks, is characterized by a good correlation between morphology and lithology: the lava flows are responsible for important plateaux, the "Planezes" having a low dip from the top centre, volcanic projections occupying the valleys. This organization is reflected by thermal zones arrangement but at night time only: lava flows are represented by a thermal low and volcanic scories by a thermal high. During the day the whole massif is represented by the some thermal low.

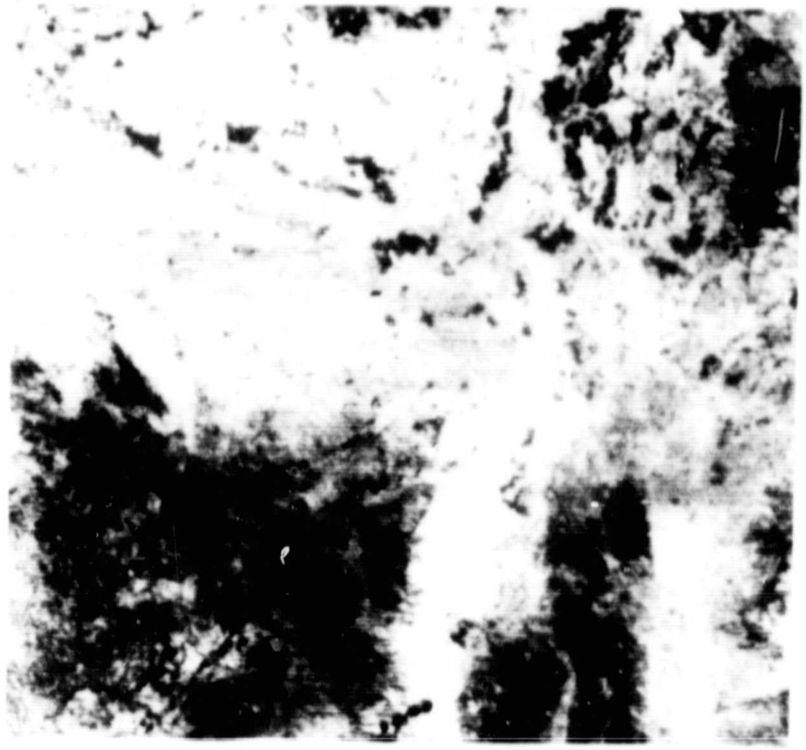
- The Mont-Dore massif mainly composed of Tertiary acid volcanic rocks, is outlined by lineaments, making possible differentiation with the Cantal, to the South, and by a complex thermal high and low where thermal high is dominant (night image).

- The Coiron massif, a typical-shaped lava flow, is represented by a medium thermal low (night image).

- The Aubrac is characterized by alternating narrow bands with thermal low and high, associated with basalts and scories (night image).

THE CHAINE DES PUYS

- Fig. 6 a -

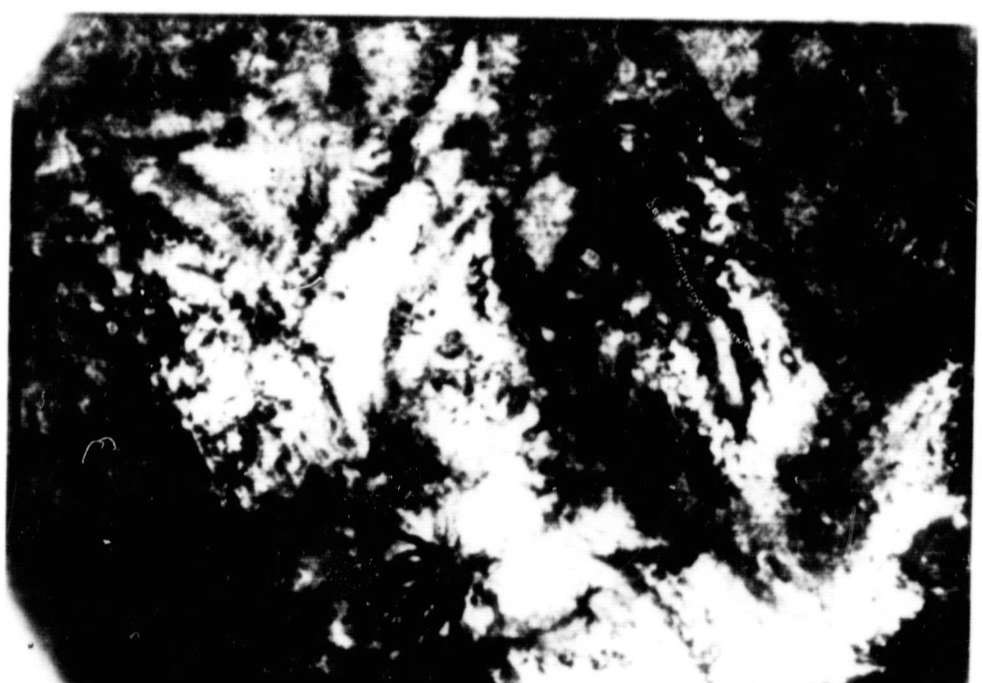


Scale 1/2 000 000
(approximate)

17 september 1979
HCMM image n° AA 50912112
Day IR

THE MONT DORE REGION

- Fig. 6 b -



Scale 1/2 000 000
(approximate)

17 july 1978
HCMM image n° AA 008202080
Night IR

2. Discrimination among volcanic rocks, according to the former section, is possible under certain circumstances, by using temperature differences. But visual interpretation limits the investigation, temperature differences being generally too small to be separated and only automatic processing could make it possible to go further. Actually, we experimented with the CNES in Toulouse, on the interactive system TRIM Alcatel, an isodensity map, but the result is not significant and we did not reach conclusions on the Brousse hypothesis.

V.2.3 - GRANITIC ROCK DISCRIMINATION

Among the granitic bodies known in the Massif Central some have been delineated by thermal signature.

1. The circular western part of the Quintin granite is associated with a thermal zone, colder than the surrounding schists. Visible during the day this difference disappears at night.

2. North of Quintin a circular thermal low is observed on day infrared HCMM images. It corresponds to the Plouaret - Belle-Isle-en-Terre granite and, according to the 1/1 million geological map of France this massif and the Quintin massif have the same age and similar petrography.

3. The Mortagne massif is revealed by thermal anomalies on different night infrared images. The observed alternating thermal high and low have a semi-circular shape and are associated with the main petrographic differences outlined (on the J.P. Renard 1/50 000 geological map (26)). This granitic body is only visible at night and has never been observed on Landsat image.

4. The Dole granite (Massif Armoricain) is visible on night image only, with a thermal high.

5. The Mont Lozere granite (Massif Central) is not always distinct from the limestones and schists. In July it is associated with a thermal low at night time. During the day it is associated with a thermal low but cannot be separated from the schists (see Plate n°3). On Landsat image this granite can be delineated on band five only, the reflectance being distinct from the schists but close to the calcareous "plateau du Causse". Actually while the "plateau du Causse" is free of vegetation, granite and schists are intensively covered with forest.

6. The Montmarault granite (Massif Central) is characterized by a thermal high, during the night only.

7. The Ambazac massif is associated with a thermal high during the night.

INTERPRETATIVE Map n°11

LEGEND

Hydrography

Thermal linear anomalies (Lineaments)

Thermal anomalies (lithology)

Date 24 September 1978

Image number AA00930-2080

Scale : 1/4 000 000 (approx.)

THE MASSIF CENTRAL TEST SITE : A THERMAL INERTIA IMAGE

Black : low thermal inertia
White : high thermal inertia

24 september 1978
HCMM image n° AA 009302080.5

V.2.4 - OTHERS DISCRIMINATIONS

Some significant discriminations have been realized in other kinds of rocks.

1. The Saint-Vincent-de-Tyrosse Miocene, north of Bayonne, was observed on a single image, in August. It corresponds to a thermal high, during night only.

According to the map it is associated with a Miocene exposure partly covered by the "Landes" sands. But, and this poses a problem, the Miocene and associated sands extend to the north, the thermal high zone stopping on a linear parallel to the regional fracturing. Vegetation and relief cannot be responsible for the difference which finally could be explained by a thickness variation of the covering sand.

2. The Libourne Eocene, north of Bordeaux, was observed in September on day image. It is associated with a thermal low. On Landsat and Tiros visible images this unit was observed during the vegetation period, crops being responsible for the visualization.

V.2.5 - ROLE OF THERMAL INERTIA

The interpretation of the HCMM images has demonstrated, mainly in the Massif Central test site, that very often geological contours have been outlined according to the rocks thermal inertia. The rocks' thermal inertia differences make possible the delineation and the discrimination of different kinds of lithological units but if this physical parameter is precisely evaluated, rock identification could be reasonably possible... But in our country according to ground surface conditions, soil and vegetation mask the rock and disturb the thermal inertia calculation. On the other hand during the investigation it has been very difficult to obtain day and night infrared image during the same 24 hours, cloud cover conditions being quite often very poor. The only example obtaine (AA 0380121502 and AA 03800011803) has not produced significant results. Being conscious that weather conditions could have changed the different used parameters during the period extending between the two selected scenes, we thereby requested NASA to process temperature difference and thermal inertia calculation for two images obtained with a 2 months interval. This has been realized on scene ID AA 0151124002, 28 July 1978 and AA 932120/3, 24 September (fig. 7).

The aim of this investigation part was to verify whether, according to the theory, the thermal inertia value could be considered as a significant one for some rocks-granites, limestones, dolomites, which are exposed on the test site. The interpretative document (I.11) reveals a spatial distribution for thermal inertia in this part of France which we have compared to the 1/1 million geological mapping. Following comments concern granites, limestones, dolomites and igneous rocks; the apparent thermal inertia reproduces the boundaries.

1. The "du Velay" and Morvan granites are visualized by their particular thermal inertia which is high, being equal to level 12 grey: this corresponds to a 152 intensity point.

2. The granites located to the west of the Massif Central present a less homogeneous thermal inertia, inferior to the former, equal to level 10 grey corresponding to a 127 intensity point.

3. The limestones are observed in two areas: le Berry and le Causse. They are both visualized by a low thermal inertia, equal to level 2 grey which correspond to a 25,4 intensity point.

According to image analysis, the Berry and Causses limestones are warm during the day and cold by night and this confirms that they have a low thermal inertia.

In the field the Causses limestones outcrop quite a lot, soil cover being absent. The Berry limestones are covered by a thin but fertiliferous soil in which limestone pebbles are numerous, brought back up to the ground surface by annual ploughing. The September image, used for thermal inertia calculation has been acquired over a soil bare of vegetation.

Dolomites, which have been separated from granite, schists and limestones by thermal differences between day, night and seasonal data, in the Causse area, cannot be distinguished on the thermal inertia image.

4. Volcanic rock discrimination is not easier on thermal inertia images. Only the Cantal massif has a distinct thermal inertia but the topographical effect cannot be neglected.

5. Some alluviums (Seine, Aube, Marne rivers) are observed by way of their thermal inertia, equal to level 6 grey levels corresponding to a 76 intensity point.

But, and this is important, it appears clearly that one single thermal inertia value cannot be significant in our country because it corresponds to an average of the associated rocks soil and probably vegetation value of this parameter. For this reason this part of the investigation has not reached valuable conclusion.

V.3 - ENERGY RESOURCES AND EXOTHERMIC REACTIONS

Several ways have been explored.

- Study of the thermal lineament significance and evaluation of their potential value in energy resource prospection.

. Sensing and analysis of thermal anomalies by reference to exothermic reactions associated with sulphide mineralizations and to geothermal prospects.

. Inventory and survey of the circular structures.

V.3.1 - THE THERMAL LINEAMENTS

Most of the observations proceed from interpretations common to several thermal images.

. In general, thermal linears were observed with an equal density on day and night infrared images with the exception of the Massif Armoricain where observations are more numerous during the night.

. Most of the thermal linears were observed on day and night images with some interesting exceptions, the north 140° oriented neotectonic faults in the Massif Armoricain. Two kinds of thermal linears have been observed on HCMM images:

- linear anomalies located in a cold or warm zone,

- linear frontiers between cold and warm zone.

V.3.1.1 - Thermal linears

Nearly all the thermal linears correspond to faults already mapped in the field. Exceptions are very significant features, some of them were analyzed in a more detailed manner and are presented in a further section (the Mont Dore geothermal prospect).

They have different signatures, four at least, according to plate n° 4.

. Most of them correspond to day thermal low changing a night thermal high.

. Some of them correspond to a day thermal high and a night thermal low (Berry-Sologne).

. A few linears correspond to a day and night thermal high.

. Some linears at least are visualized only at night, with a thermal high (North 140°, in the Massif Armoricain). Other signatures possibly exist but have not been observed yet. A first attempt to search for the significance of these different thermal fault characteristics reveals two possible explanations which have to be explored.

1) Water content and this could be very interesting for water supply in fractured rocks, mainly in the basement.

2) Neotectonics.

Plate n° 4

Fault	Day thermal signature	High thermal signature	Associated relief
Sillon Armoricain	thermal low	thermal high	hilly range
Sillon St Georges	thermal low		hilly range
Sillon houiller	thermal low	thermal high	no
St-Etienne	thermal high		scarp with north illumination
Brevenne	thermal low	thermal high	
Sillon d'Avranches	thermal low	thermal high	
Pays de Bray	thermal low	thermal low	
North 140° (Bretagne)		thermal high	
Argentat		thermal low and high (seasonal effect ?)	
La Vilaine		thermal high	
Nogent-le-Rotrou		thermal low	
La Marche		thermal high	
Les Andelys		thermal low	
Montreuil-Bellay		thermal low (February) thermal high (July)	
Sologne-Berry	thermal high	thermal low	
Nord-Pyrénées		thermal high	

V.3.1.2 - Linear frontiers

This kind of thermal linear is not always associated with nown faults but where it is, the associated fracturing corresponds to horsts, graben or rock units contacts.

In general, all the known Tertiary graben in the Massif Central are represented by linear frontiers between two thermal domains. Some of these features were studied in detail because they present a particular interest, from a general geological point of view. Two of them have been mentioned in section V.1 because they are outlined first by a meteorological effect. But a tectonic reason could be completely excluded according to a more detailed analysis.

The first one, actually, can be considered as a southwest extension of the Nogent fault, the northern part of the Sillon houiller. The thermal frontier is associated first with the Nogent fault itself which extends further to the south west where no fault has yet been mapped in the field. The thermal phenomenon is very obvious, thermal high to the west, thermal low to the east. According to the geological map this frontier is not associated with a lithological change or a tectonic feature but it is also visible on Landsat and has been discussed (Scanvic 4). It corresponds to a small hilly region associated with a change in the hydrographic pattern rivers running to the west and to the east along the thermal contact. Last, but not least, in August 1978 and July 1978, two periods during which thermal frontiers were observed, the meteorological map (38) outlines by isohyets a water precipitation change parallel to the anomaly.

Once again this example demonstrates the complexity of the phenomenon responsible for observe thermal differences. A tectonic exploration cannot be excluded but hydrology, relief and meteorology have probably contributed to the final signature.

The second anomaly is located on the southern limb of the Massif du Cantal; here again there is a change in the hydrographic pattern but fracturing cannot be completly excluded.

V.3.1.3 - HCMM contribution to the Mont Dore geothermal prospect study

B.R.G.M. and the European Economic Community have carried out a geological survey of the Mont Dore area, France. The aim was to determine the geothermal potential of this volcanic massif, Tertiary in age. Geophysics, hydrogeology, tectonics, remote sensing were used to arrive at the result.

In particular all available remote sensing techniques contributed to the survey: aerial photographs, Landsat MSS and HCMM thermal

images, side looking radar. Significant results have been obtained (27) from the interpretations realized in the early stage of the field campaign and confronted with the other techniques on a 1/50 000 scale. The major structural features were revealed by remote sensing and confirmed by geophysics or field evidence. The final map reflects the remote sensing interpretations with a certain accuracy and represents a completely original document, few fractures being mentioned on previous data (28). The main results are the following:

. Aerial photographs

Black and white photographs, 1/25 000 scale were interpreted. Four fracture directions were outlined and later found on the field:

- North 60° and North 110°, Hercynian fractures in the basement,
- North 20° and North 170°, Oligocene and Quaternary fractures.

However, from this interpretation it has been difficult to determine the importance of the different fractures.

. Landsat multispectral image (I.12)

Standart NASA products recorded at different epochs have been interpreted. According to this interpretation some of the North 60° and North 170° fault directions correspond to major lineaments, and are associated with magnetic discontinuities. This fracture pattern is fairly interesting for two reasons.

- The numerous thermo-mineral springs known in this region are located along some of these lineaments, making it possible to get an idea of their regional tectonic control, unknown until now.

- It composes the Caldera walls, outlined by geophysics. On Landsat image lineaments visualized at least three sides of the Caldera.

Moreover a circular structure, visible on Landsat and aerial photographs was discovered and corresponds to an ancient and wide volcanic cone, partly weathered, unknown until now (I.12).

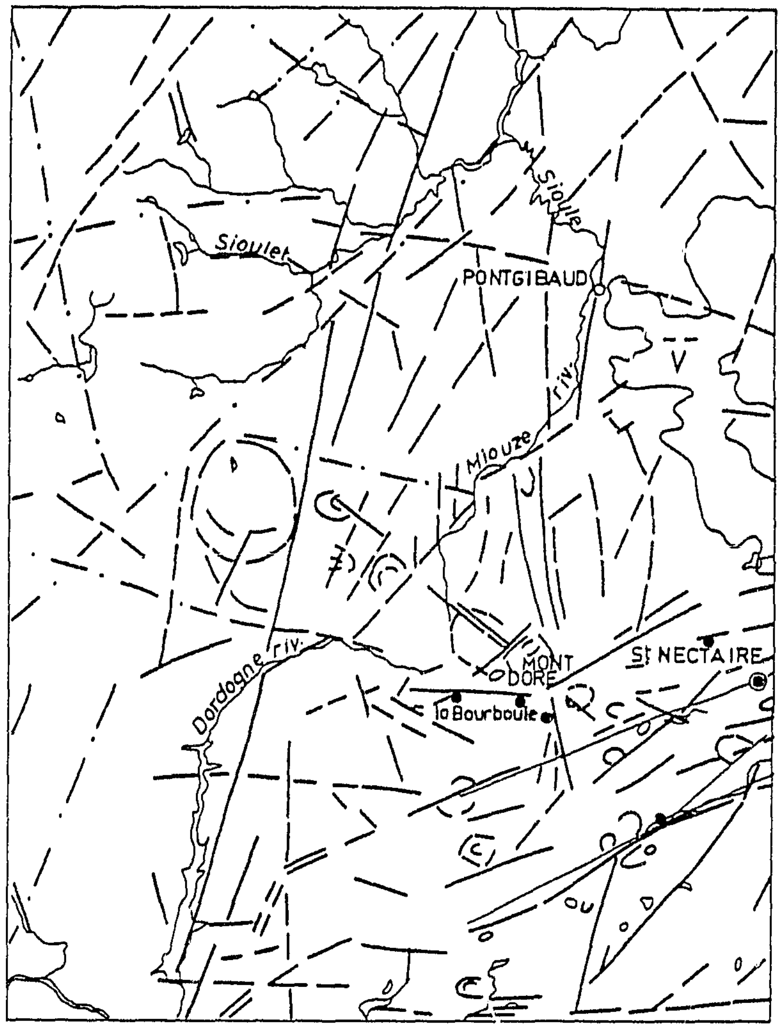
. HCMM images

Four thermal images covering the Mont Dore area were interpreted with a certain amount of detail: three of them are night infrared images one is a day infrared image.

The day thermal image, taken in September 1979 is not interesting and the only night image makes possible a significant interpretation. New litho-structural features have been outlined which have not yet been checked in the field: but they fit in very well with the regional structural context, according to the geological map. They represent significant results and are pictured on interpretative map n° 13.

INTERPRETATIVE Map n° 12

ORIGINAL PAGE IS
OF POOR QUALITY



LEGEND

Hydrography

Lineaments (Landsat)

Circular structures

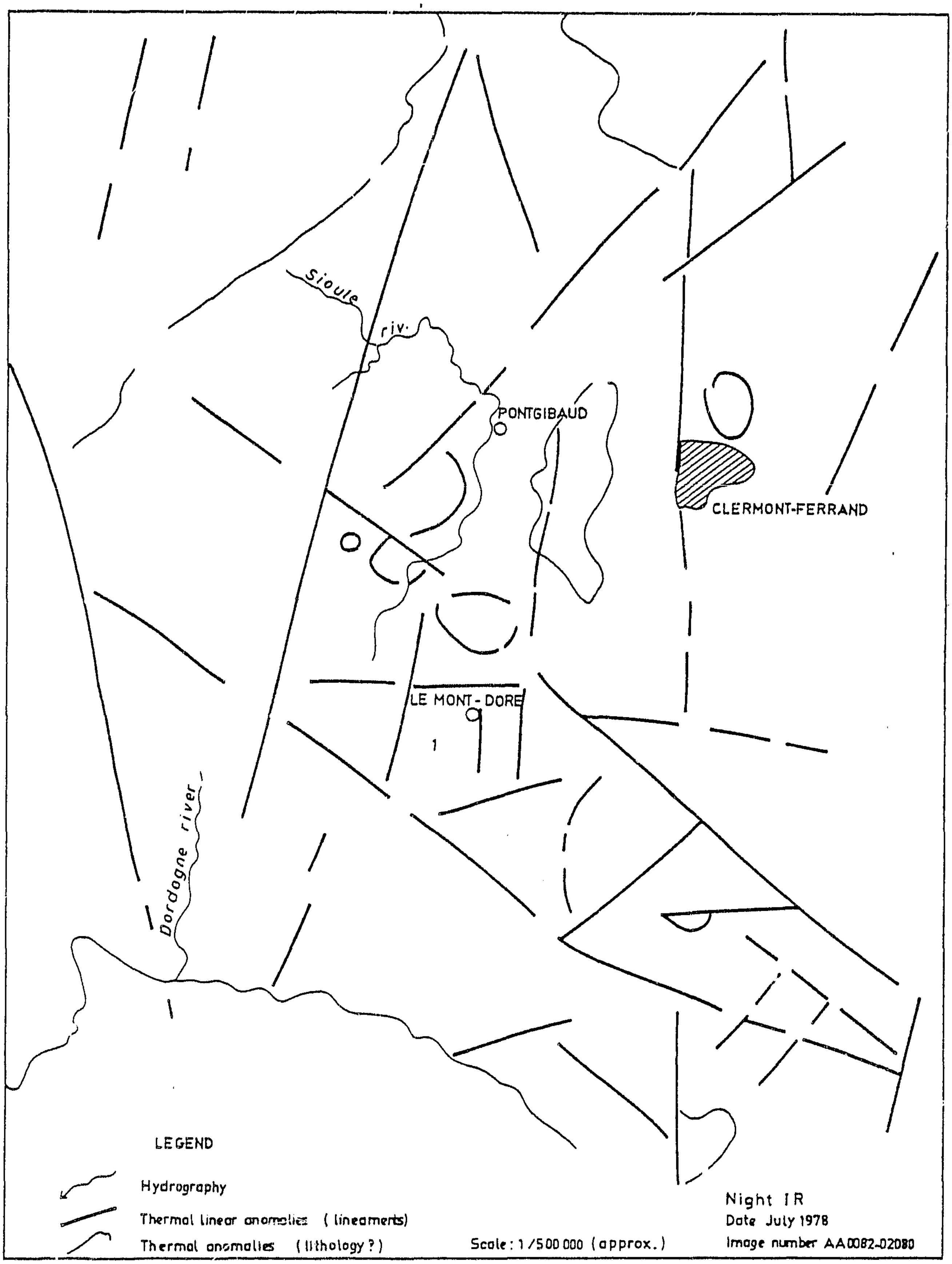
Aeromagnetic discontinuity

Chaîne des Puys Volcanism

Thermal springs

Scale : 1 / 500 000

INTERPRETATIVE Map n° 13



On the July 7th, image, thermal zones and thermal linears outline the key location of the Mont Dore Massif at the intersection of the North 10°-20° Oligocene faults and the North 170° Hercynian fractures which are both responsible for a system of horsts and graben: until now this was only a hypothesis and can be considered as a valuable contribution from HCMM image interpretation.

On this image thermal linears picture the caldera walls on its four sides.

On the July 17th, image (Fig. 6B) which has been enlarged twice, the fracture pattern (I.13) confirms the former interpretation and outlines a tectonic relationship between the Margeride and the Mont Dore by way of the 110° North direction. This new observation is a valuable contribution to the regional structural scheme comprehension. Moreover, this fault system is continuously visible on thermal image even through the basaltic lava flow forming the Cezallier plateau: this can be considered as the result of heat transfer from the basement to the surface.

On the same image, thermal zone distribution corresponds to the rock units distribution, according to the geological map. In particular the acid volcanics outcropping in the centre part of the Massif are responsible for at thermal high.

Finally, this image reveals, in the northern part of the massif, on annular structure enhanced by alternating thermal high and low. This structure is located to the north of the known caldera.

On the November image the North 110° fault direction is quite visible and separates the basaltic lava flow into three thermal zones:

. thermal low to the south,
. thermal high to the north east,
. thermal medium low to the north west.

The significante of these differences is not known but could be attributed to some basement differentiations:

Lastly, the southern part of the Limagne valley, a Tertiary graben, confused on former images, is very well delineated on this document.

. Side-looking radar

This coverage has been carried out by the French army with Emi-Electronics system. It was interpreted by R. Brousse and S. Paul (29). Certain linear discontinuities were observed for they have a distinct signature and have been discussed by the authors.

V.3.2 - THERMAL ANOMALIES AND EXOTHERMIC REACTIONS

Two points are discussed in this section.

. HCMM sensing ability for thermal anomalies potentially associated with exothermic reactions of sulphide mineralization.

. analysis of thermal anomalies discovered during the survey.

V.3.2.1 - Exothermic reactions of sulphide mineralisations

Experiments have demonstrated that a heat transfer exists, from subsurface to ground surface, in certain circumstances, which could be remotly sensed by way of thermal infrared airborne records. This ability has been searched for on HCMM data for some test sites where sulphide mineralizations are known and because this kind of mineralization could be responsible for a sufficient heat flow.

The proposed test sites are Chiseuil (Massif Central) and Bodennec (Massif Armoricain). They have both been studied intensively in the field and by different remote sensing techniques to support the HCMM investigation. A last test site was selected in Decazeville, a coal mine. Theoretically HCMM spatial and thermal resolution are adapted to the size of the test sites and to the heat transfer amplitude but, due to the broad HCMM scale and the geometric accuracy, the eventual anomalies cannot be precisely associated with the target.

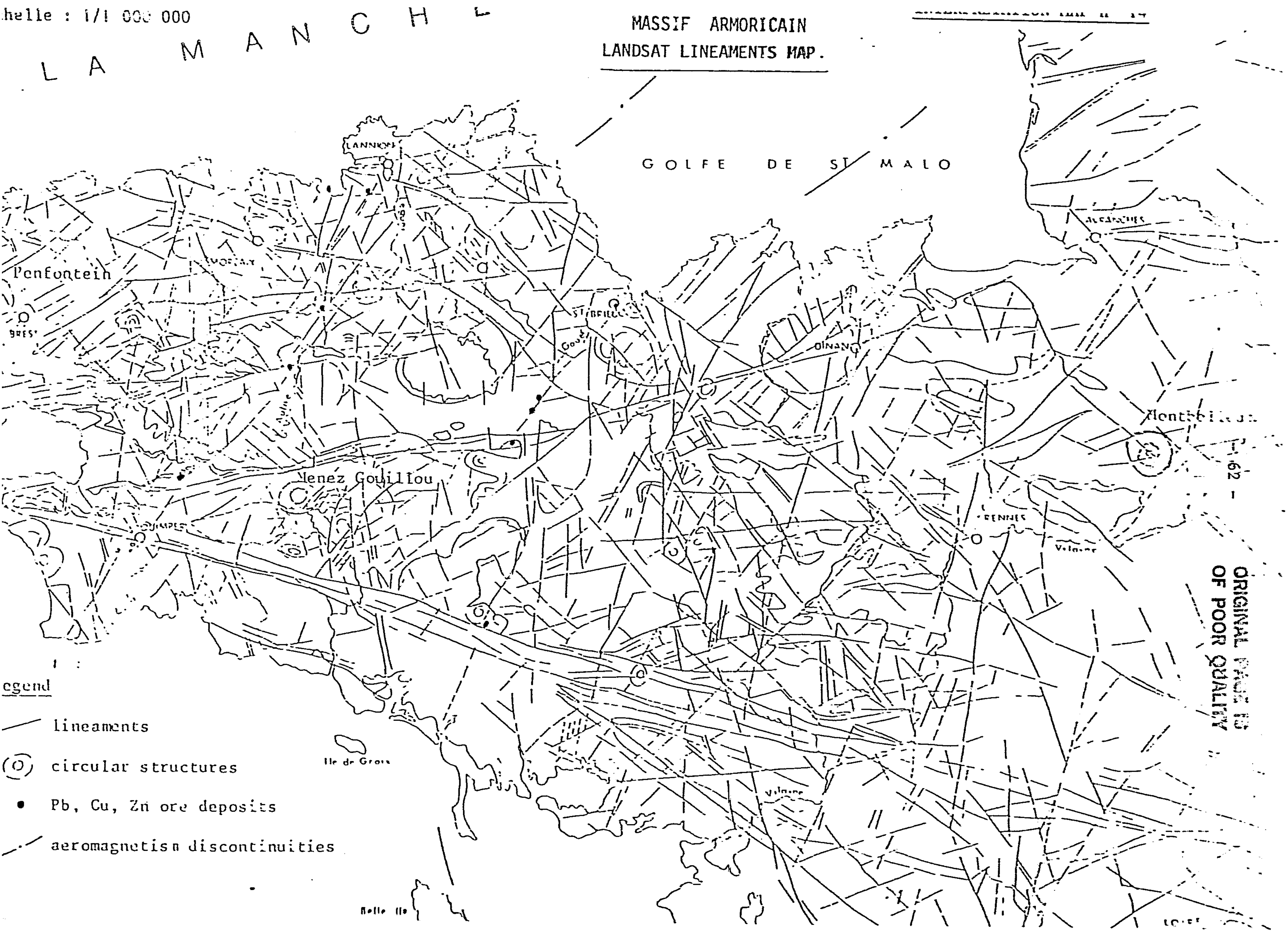
- Chiseuil was selected for several oxydized sulphides have been exploited and tips are known in the vicinity of the main ore body.

Aerial photographs 1/25 000 scale and Landsat images were interpreted and compared with previous geological mapping. From aerial photographs and Landsat interpretation a North 10° and North 60° fracturing was outlined, the Chiseuil prospect being on a crossing of these two fault directions.

On the HCMM image a thermal linear frontier is observed between a thermal to the west, a thermal high to the east, outlining a main north 10° fracture. This discontinuity is apparently associated with a lithological change, granite rocks to the east, sedimentary layers to the west. But the Chiseuil body is located in the granitic complex, associated with a thermal high and so significant differences cannot be observed.

- Bodennec is part of a Cu, Pb, Zn district, lying in a volcano sedimentary unit, and recently discovered by B.R.G.M.. The ore body is known by geophysics and drilling and a spontaneous polarization was observed which could be responsible for a possible heat flow. The Landsat image interpretation is at the origin of an important contribution to the

MASSIF ARMORICAIN
LANDSAT LINEAMENTS MAP.



knowledge of the spatial distribution of the deposits (30). All these mineralizations are located along two north south discontinuities and generally at a crossing point with a North 70° fault direction (I.14). The North south fracturing is not mentioned on the geological map but

. it corresponds to magnetic discontinuities in the sea (Channel and Atlantic ocean),

. in some prospects detailed mapping confirms that such a fault direction exists and indicates its importance for it corresponds to a permanent structural axis (Cambrian to Devonian) along which several volcanic events of various ages are located.

Lastly, these two lineaments are now considered by geologists as a very important paleo crustal failure which could have been a guide for the mineralizations.

The HCMM image interpretation is not very interesting probably because of the medium image quality. Only the 70° north direction was observed and no obvious thermal anomaly was discovered.

- Decazeville test site was selected because it is an open cast coal mine. On the HCMM image a thermal high was observed in the vicinity but once again it could not be accurately associated with the mine.

V.3.2.2 - Thermal anomalies

The HCMM image analysis revealed anomalies, thermal highs or lows, the existence poses a problem. These anomalies have been classified into several groups:

A - anomalies inside the same geological formation

B - anomalies between thermal signatures of some rock units

C - thermal anomalies.

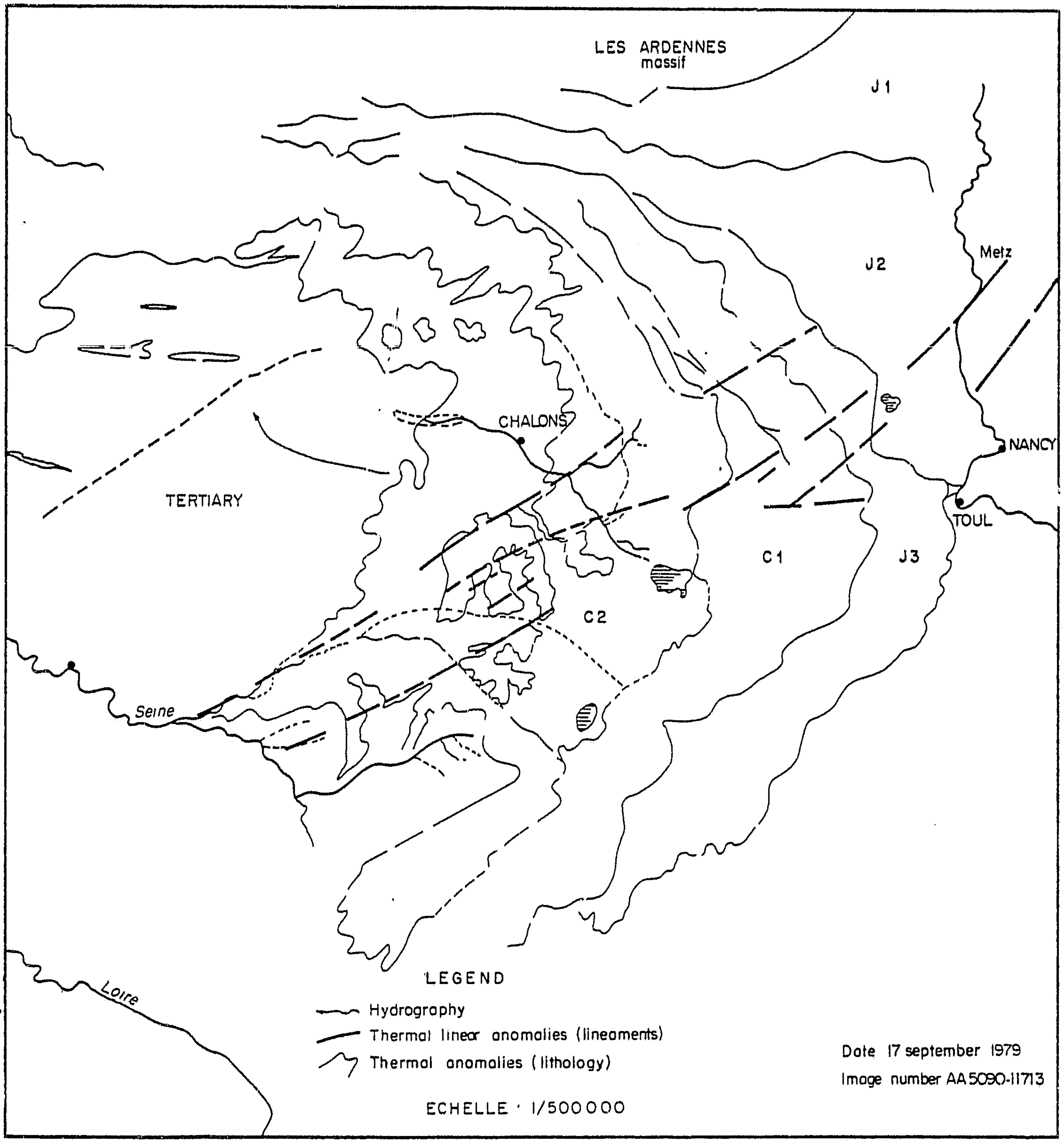
A) Two very important anomalies were detected in the same geological formation.

- The granite de Montmarault (Allier, France). This granite is composed, according to recent geological mapping of two branches, the eastern and western one. On the night image only the eastern branch is visualized (6 - I.8b) with a certain accuracy, this not being explained by relief, vegetation and petrology.

- The Cretaceous chalk of the Paris Basin formation is perfectly remotely sensed by Landsat and also presents a characteristic thermal signature (on both day and night images). But a clear thermal high unit, concordant with the main structure, oriented parallel to the Jurassic,

THE "BASSIN DE PARIS"

INTERPRETATIVE Map n°15



Cretaceous, Tertiary beds, was delineated on a night image (33 - I.8b and 15). Good geological mapping and the hydrogeologic map does not yet give the significance of this anomaly : studies are in progress to explain this phenomenon which is not visible on the good Landsat image we have.

B) Different anomalies were observed between the thermal signatures of apparently similar formations.

- On the same night image granitic bodies have distinct signature (I - 8b).

Montmarault (6), Dole and Dinan (7), Ambazac (8) are represented by a thermal high.

Les Pieux, near Cherbourg is visualized by a thermal low.

Sanvensa, near Villefranche-de-Rouergue is associated with a thermal low in the north, a thermal high in the south. For this granitic massif the thermal difference can be explained, but this has to be checked more precisely, by the lack of alterite in the north.

- On the night image all the coastal swamp (I - 8b - 9 to 13) presents a characteristic thermal low signature with the exception of the major one in the Niort area (16).

C) Thermal anomalies.

HCMM image analysis has also revealed thermal high zones which cannot be explained by meteorology, vegetation or lithology.

Actually, meteorology is not responsible for these thermal zones because they have a definite shape and size which are unusual for this kind of temperature difference (that is experience of meteorological effect and comparison exclude this possibility) and they have also been observed, more or less with the same shape but with a few variations, on several images at different epochs.

Forest vegetation cannot explain it for two main reasons.

- in general, the main forests known over France are associated with a thermal low at night with a few exceptions discussed in chapter V.1.,

- if a forest is associated with the anomaly it is generally not restricted to it.

Lastly, according to the geological map, there is no lithological change corresponding to the delineated anomalies.

Six anomalies were studied in detail:

1. Pays de Bray south east

Lithology: Cretaceous limestones

Relief : Any characteristic topography but the anomaly is accurately located between two small visible rivers, the Apte to the east, the Andelle to the west.
The de Lyon forest occupies the whole anomaly but extends outside it.
The anomaly is visible both on night and day thermal images.

2. Pays de Bray south west

Lithology: Cretaceous limestones

Relief : None, except the scarp forming the southern limb of the Bray outicline. Note: this scarp is represented by a thermal high which contrasts with the thermal signature of the northern limb (same lithology, no thermal expression at the scarp level).
Lastly, a forest exists (Eawy forest) on, and outside the anomaly which appears on day and night images.

3. Château sur Loire

The anomaly is in Cretaceous limestone and it is associated with the forest of Berce which extends further. This forest corresponds to a thermal low outside the structure.
This anomaly is only visible on night images.

4. La Flèche

Lithology: Cretaceous limestones

The anomaly is located between the Loir (south) and Sarthe rivers (north). Topography and vegetation, there is no forest in the region, so this cannot explain the thermal zone; the characteristic shape is visible on the night image only, but at different epochs.

5. La Rochefoucault

Geology : microschists to the south, gneiss to the north, according to 1/50 000 scale map.

Relief : very little difference exists.

Vegetation: lack of forest.

The anomaly is only visible on the night image.

6. Charlieu

Geology : granites and Jurassic.

Vegetation: lack of forest.

Relief : similar to the surrounding country.

The anomaly is only visible on the night image.

V.3.3. - CIRCULAR FEATURES

The importance of circular structures in France was revealed by Landsat B.R.G.M. project (4 and 5) and further field mapping (18) or bibliographic studies have shown the geological nature of some of these features: they have various origins but, where they have been explained by lithology, tectonics, geophysics or geochemistry, they represent a valuable contribution to geological mapping of the country. Our purpose in this section is to discuss some structures detected on HCMM and Landsat images.

V.3.3.1 - Landsat and HCMM common circular structures

Only a few structures have been detected both on Landsat and HCMM. They are located in Riom, Quintin, Villefranche de Rouergue and Montmarault.

1. Riom

The feature is located in the Limagne Tertiary graben. It is revealed by a circular reflectance zone on the 1 242 100 82 image, band seven only: this excluds a vegetation effect.

According to the 1/50 000 scale geological map (31) it cannot be explained by a lithological change and the topography is uniform, the area being flat in and outside the structure.

But the isobath map drawn up from geophysics and drilling loggings, outlines a surimposition of the surface anomaly over the deepest part of the subsidence (32).

Moreover, the geotechnical map of Clermont-Ferrand (33) presents a concordance between the structure and a zone characterized by drainage and soil moisture.

Lastly, hydrogeologists have described in the region several springs with an abnormal chloride content, compared to the surrounding:

The last two observations could be responsible for the reflectance anomaly on the surface and W. M. Robert (34) proposes a general

explanation of water movements in subsidence basins which explains the relationship between a buried structure and the ground surface revelation. This author assumes that upward movement and discharge of waters from depth are very important and are responsible for moisture content elevation on the surface, with a circular or oval shape.

In conclusion he says that change of salinity and temperature may be observed in such occasions.

According to this assumption, partly confirmed by hydrogeologists (salinity) it was reasonable to look for a thermal anomaly near the structure. On a temperature map drawn up by the Ecole Nationale des Mines of Paris (35) a thermal difference is visible about on the circular structure location and a circular structure outlined by a series of annular thermal low and high has been observed on HCMM images (section III.2): but once again it is difficult to certify the location accuracy.

2. Quintin

This structure was studied in detail in a former section (4.1). Visible on Landsat (3), explained by further field mapping (18) this feature is associated with a thermal low, visible only on day thermal image.

The eastern part of the granitic massif in which the structure is located has never been observed either on Landsat or on HCMMS.

3. Villefranche-de-Rouergue

Discovered on Landsat image (4), this structure was described by Brosse (2) and recent investigations (39) have outlined its origin. It is associated with a granitic cupola. Thermal evidence of this structure was found on night HCMM image.

4. Montmarault

This anomaly was discovered both an aerial photographs and Landsat image (36). Field investigation outlined that it corresponds to a caldera.

Finally, it is associated with a circular structure, a thermal medium high, and on night image only.

V.3.3.2 - Other circular structures

Several circular anomalies were observed on HCMM images. All of them are represented at different epochs, as mentioned in section III.2.

They present two main characteristics

- they are only visible on night images,

- they are generally composed of a series of annular thermal highs and lows. In general they are formed by a thermal low central ring, then a thermal high.

The main structures discovered are located:

1) in the eastern Massif Central (two),

2) in the Cezallier plateau,

3) in the Mont Dore area,

4) in the Bassin d'Ebreuil,

5) in the south east of the Les Andelys fault (I.9 point 8).

Significance of these structures has been searched for on the geological map.

1) They are located in a granitic massif intruded by volcanic rocks.

2) The Cezallier plateau is a basaltic lava flow, the structure could have a volcanic origin.

3) The structure could be associated with a visean granite, in the Cisternes village. This granite is cut by two faults visible on HCMM images.

4) Is located in Tertiary limestones.

5) Both structures are located in sedimentary layers.

V.4 - CHANGE DUE TO SPATIAL RESOLUTION

Documents used to achieve this section have different origins. First is a France Landsat mosaic composed of 40 images, spectral band 7, and reduced to a near 4 million scale. Then Tiros N and Noaa visible images of the whole of France, which are recorded at the Lannion station (France) have been used. By courtesy of the "CMS and Meteorologie nationale" (France) B.R.G.M. has received some of them, free of clouds and interpretation has been achieved, making possible a comparison with HCMM visible image (Fig. 8).

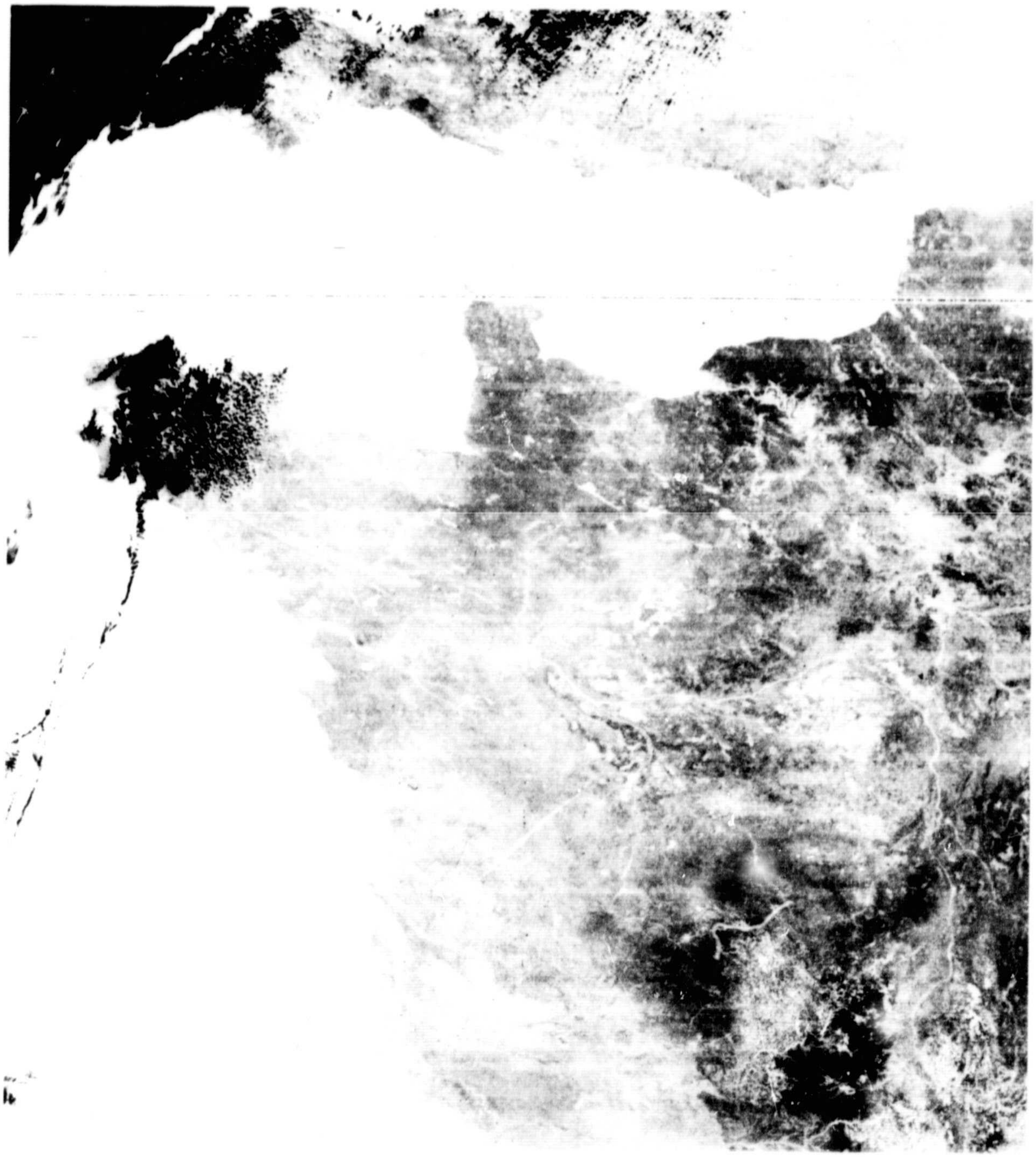
In general HCMM visible images are not very contrasted (Fig. 9) making them difficult to study. We also selected some significant geological details, according to the geological map and their visibility on the different remote sensing documents, and we surveyed their signatures.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

TIROS N VISIBLE IMAGE

METEOROLOGIE NATIONALE
CMS - Lannion - France

5 september 1979
TIROS N image
Visible channel n° 1



7 september 1980
HCMM image n° AA 865-12073-6
Day visible

Plate n° 5

	LANDSAT	TIROS N (SEPT. 1979)	NOAA (JULY 1975)	NOAA JULY 6, 1980	HCMM
LITHOLOGY					
ARDENNES	Visible	Not visible		Visible	
CANTAL VOLCANIC	Visible	Not visible		Visible	Visible
LES LANDES	Visible	Not visible	Visible	Visible	Visible
LIBOURNE (MIOCENE)	Visible	Confused	Visible	Visible	Visible
MONTAGNE NOIRE	Visible	Visible		Not visible	Visible
CHAINE DES PUYS	Visible	Not visible		Visible	Not visible
AUBRAC	Visible	Not visible		Visible	
PAYS DE BRAY	Visible	The associated fault is visible		Visible	Not visible
BASSIN DE PARIS (CRETACEOUS)	Visible	Visible but confused	Visible	Visible but not really distinct	
BERRY (CALCAIRE)	Not visible on spectral band 5	Visible	Visible	Visible	
LES CAUSSES	Visible	Not visible		Visible but not really distinct	
TECTONIC					
SILLON ARMORICAIN	Visible	Visible		A part of	A part of
FAILLE DE VILLEFRANCHE	Visible	Visible but confused		Not distinct	Visible
SILLON HOUILLER	Visible	Not visible		Not distinct	Not visible

Results are summarized on plate n° 5.

They make it possible to conclude that:

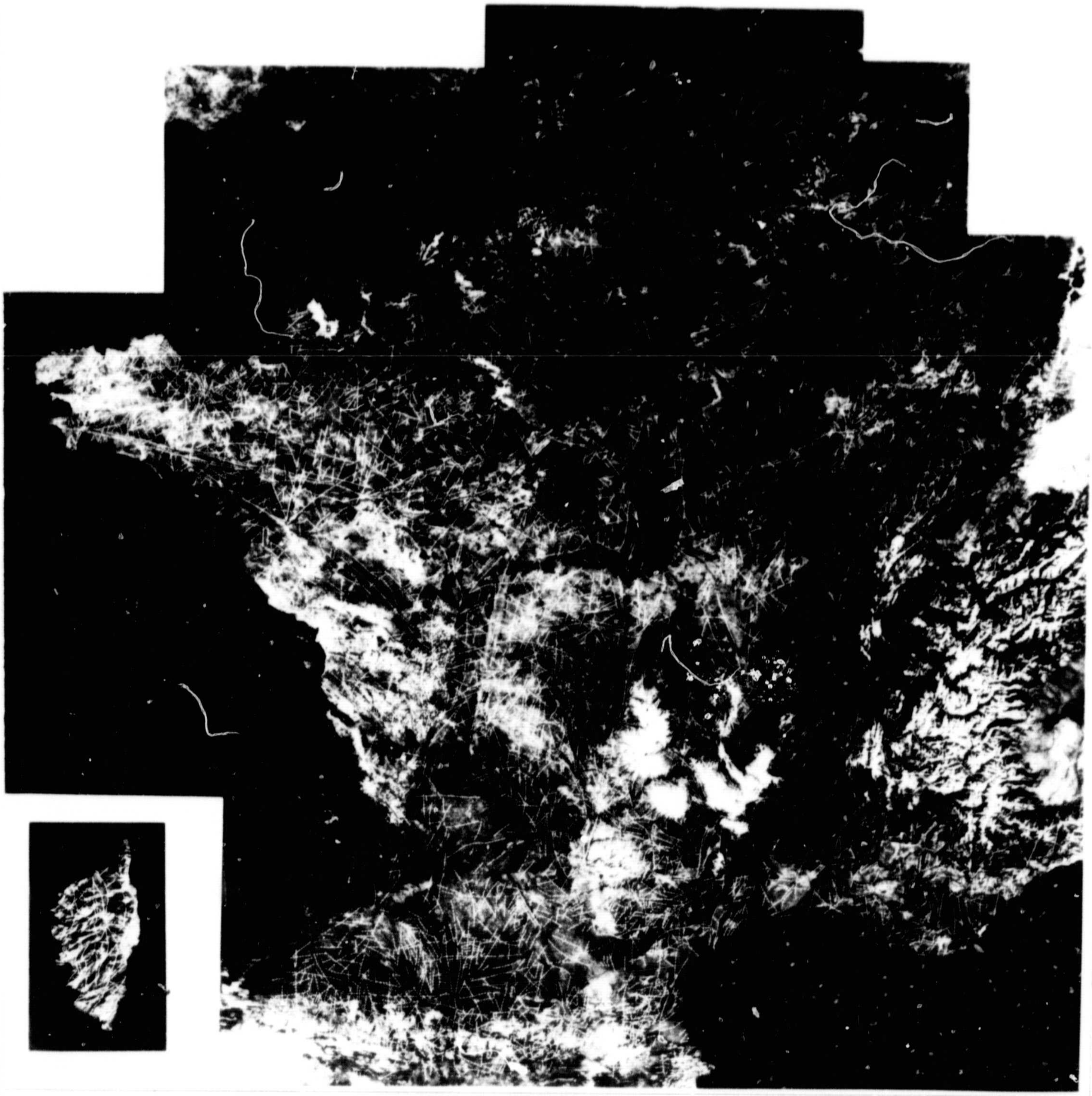
- A degradation exists compared with Landsat. Figure 10 which represents a Landsat mosaic of France with surimposed lineaments, illustrates this degradation. In the Villefranche-de-Rouergue massif where a characteristic circular structure was discovered on Landsat (2) the degradation is important on visible HCMM data, this structural detail not being observed. But, according to the accuracy of the data it seems the structure corresponds with a thermal circular zone (I.2). This example, and others, demonstrates the importance of the thermal resolution compared to the spatial resolution.

- Even if the geological details which can be observed are nearly the same as the one observed on Tiros and Noaa, HCMM visible images are in general poorly contrasted, making interpretation difficult. Compared with HCMM thermal images results are not significant.

FRANCE FROM LANDSAT

A STRUCTURAL INTERPRETATION

LA FRANCE VUE DE SATELLITE



CONCLUSION

- This investigation has been difficult to achieve for general weather conditions were poor during acquisition time. But at last the two test sites, the Massif Armoricain and the Massif Central (FRANCE) have been completly surveyed with day and night thermal images. One of which were acquired during the same 24 hours, with on acceptable cloud cover (17 sept. 1979) but due to a long time delivery thermal inertia has not been processed.

- The survey consisted mainly in a visual interpretation of photographic documents obtained from NASA and ESA, to the exception of one experiment with CNES and GATA, to perform a digital processing on an interactive system. All these interpretations were compared with published geological maps, HCMM image distortion making difficult this very important part of the investigation. Lastly, temperature differences and thermal inertia maps were generated by NASA over two scenes.

- Significant geological observations and results were made and obtained from standard images but production of other kinds of documents not having been realized from optimal quality data, no valuable conclusions have been reached with them.

. Thermal zones delineated on single day or night images generally correspond to lithological units, according to the 1 million scale geological maps, with the exception of some of them which reflect ground atmospheric conditions: to avoid this confusion, interpretation has to be achieved by comparing multi-seasonal images.

Apart from this exception lithological mapping was prepared from thermal difference delimitation, according to three criteria.

Thermal differences common to day and night images, throughout the year.

Thermal differences observed on a single day or night image only.

Thermal differences observed on a definite seasonal image.

On the two selected test sites, granites, carbonate and volcanic rocks were delineated and discriminated with a fair accuracy, in function of the scale, through their thermal effect. It has been demonstrated that this thermal effect is evolutive in function of day, night and seasons, because of thermal inertia and earth surface conditions, soil moisture content playing an important role. The follow-up of this thermal evolution made possible rock discriminations which are not observed on Landsat visible images, the Mortagne and Montmarault granite for instance. But multi-

seasonal thermal mapping is difficult to achieve with accuracy by the visual way only and could be improved a lot by computer processing making possible:

. Geometrical correction of distorted image and then, superposition extraction of visual temperature differences.

. Thermal inertia calculation and visualisation have been experimented and under some conditions, not realized in this survey, could make possible rock identification and correlation. In European countries and more particularly in France, rocks outcrop very little, soil and vegetation creating a mask. But some examples stress that heat flow from rocks can be transferred through soils and revealed on the earth surface by the radioactive balance which is taken in account for the interpretation. This radioactive balance is the final result of a cumulative effect sensitive to moisture-content soil surface and vegetation variations. This experiment has proved lithology mainly influences this radioactive thermal balance and for this reason the use of thermal inertia to correlate and indentify rock units is suitable if it is calculated on day, night, seasonal data, making it possible to reach a statistical value of the parameter. As a consequence of thermal inertia seasonal evolution, a dolomite limestone's discrimination has been made by day and night temperature differences at different epochs, data not being acquired on the same day.

. Thermal differences are also at the origin of significant structural geology information. Actually new features are very rare, compared to the one discovered on Landsat visible images and they nearly always correspond to important known fractures. Even some basement faults have been revealed through a basalt flow. The interest of this information is in the thermal mode which reveals linears, this being probably very important for it could be characterised in terms of neotectonics and drainage ability, a valuable detail in basement rocks water research.

Two categories of thermal linear have been observed:

1) Low or high linear thermal differences included in a warm or cold zone.

2) Linear frontiers between different thermal regions. The first class, according to the survey is quite often associated with known fractures, the second being generally correlated with faulted geological boundaries.

Linear thermal differences have been differentiated into four categories:

- linears represented by a thermal low during the day, a thermal high at night (Sillon Houiller),
- linears represented by a thermal high during the day and a thermal low at night (Sologne),
- linears represented by a thermal high during day and night,

- linears represented by a thermal high during the night only North 140° in Massif Armoricain.

These observations have been made on several images but the possibility for a seasonal variation existing has not been fully surveyed. Moreover these linears have to be investigated in the field to explain the associated thermal effect significance.

At least a significant preliminary result has been obtained over the Massif Armoricain where fractures, known as neotectonic, are only visible with a thermal high during the night, most probably because they could emanate Radon gases which could be responsible for this specific thermal effect.

Thermal frontiers have revealed the best known Tertiary graben. In the Mont Dore region similar features have been observed on several images and they could correspond to this tectonic style. They have no correspondance on the recent tectonic map but are coherent with it, making it possible to replace the Mont Dore Caldera in an original tectonic scheme which appears very significant for the search of geothermal prospects.

. Thermal anomalies have been searched for as a guide for energy ressource prospection. Actually sensing of exothermic reactions associated with sulphide deposits has not been demonstrated, most probably because it is difficult to accurately locate small observed thermal differences which could translate such phenomena up to the ground surface. In the future such a study has to be realized by computer processing based upon geometrical correction and quantitative temperature maps. But, and this is a very significant result, other thermal anomalies have been discovered which represent an interesting way for future research. These anomalies are of three kinds:

- anomalies in a same rocks unit: the one discovered in the Basin de Paris is promising enough to justify new field investigation in a region mapped at a 1/50 000 scale,

- thermal anomalies not associated with a special lithology. This kind of anomaly has to be carefully investigated to understand the phenomenon and outline its scientific interest,

- circular structures, at least one of them being associated with a caldera.

Changes due to spatial resolution are evident, differences being important between HCMM and Landsat visible image interpretation. In general, details observed on HCMM visible images are similar to the one visualized on Tiros and Noaa, but the average quality is not good, contrasts are poor, this making difficult the interpretation.

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